
# Advanced Inverter Technologies Report

## GRID PLANNING AND RELIABILITY
## ENERGY DIVISION

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## Executive Summary

This report examines the present and evolving capabilities of advanced inverter technologies for both primary and secondary distribution applications. Inverters are power electronics-based devices which convert direct current (DC) to alternating current (AC), a function which is fundamental to the integration of power from many sources into the distribution system. Inverters are widely used in conjunction with a range of Distributed Energy Resources (DER), particularly photovoltaic and wind turbine generators and energy storage resources. In these applications, inverters convert a generated or stored DC to a precisely modulated and grid-synchronized AC waveform. This waveform's frequency is to be identical and to the grid frequency, enabling the supply of this electric power to an interconnected load or into the distribution system. Beyond this fundamental purpose and the requisite functionalities that this purpose entails, there exist a range of complementary, technologically viable, and demonstrated functions that an inverter may be designed to provide, including the following:

I. Reactive Power Control. An advanced inverter has the ability to supply or absorb reactive power, measured in VARs, in the desired quantity. This provides for more efficient distribution and improved power quality.
II. Voltage and Frequency Ride-Through Responses. In the presence of fluctuations in the distribution system's voltage or frequency, this advanced inverter function seeks to correct the fluctuations by modulating reactive or active power, respectively. In the case of temporary and resolvable conditions, this can allow the DER to continue operation through a fault.

Advanced inverter functionalities represent a significant opportunity to improve the stability, reliability, and efficiency of the electric power distribution system, particularly as DER become incorporated onto the grid at higher penetration levels. Autonomous implementation of advanced functionalities could provide localized nodes of stability and control on a distribution feeder. When coupled through sophisticated communication, augmented protection, and intelligent control, interconnected advanced inverters could have significant beneficial impact upon the efficiency and reliability of the distribution system. Utility distribution automation or distribution management systems will be central to the integration of these functionalities, enabling necessary and sufficient communication, protection, and control measures.

Despite proof of concept by national electric power systems in Europe, implementation of these functionalities is not presently supported by the standards which govern inverters in the United States, preventing both widespread adoption of these functions and realization of the corresponding benefits to the distribution network. In addition, there is a lack of consistent U.S. interoperability and performance standards for inverters and inverter controllers to communicate with utility distribution management systems. This discrepancy will make full realization of the potential benefit of advanced inverter functionalities difficult, especially in the context of safely and reliably enabling higher penetrations of distributed energy resources.

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# 1 Technical Background on Inverters

## 1.1 Standard Inverter Key Concepts

Fundamentally, an inverter is a device which converts a direct current (DC) input to an alternating current (AC) output. Historically, devices that converted AC to DC were called "converters" and therefore devices that did the reverse (i.e. DC to AC) were called "inverters". Inverters are used in a range of applications, including consumer power electronics, electric vehicles, and photovoltaic and energy storage interconnections to power distribution systems at the primary (4 kV, 13.8 kV, 27 kV, and 33 kV) and secondary (120/240 V, 120/208 V, 240/480 V) levels.

In distribution applications, these devices produce a sinusoidal waveform of the appropriate frequency, typically through power electronics-based implementations of controlled, sequential switching. Inverters may stand alone (i.e. off-grid) and supply generated power solely to connected loads, or they may tie into the grid and allow generated power to be supplied to a utility's distribution network when not needed by the load. In either case, an inverter may be coupled with an energy storage device, such as a battery, and retain power generated for later use, thus mitigating intermittency of the generator and improving response to power demands. The necessary conversion enables the supply of real power to the electrical distribution system or to everyday loads.

## 1.2 Standard Inverter Functionalities

In compliance with standards developed and adopted by Standard Development Organizations (SDOs) such as the Institute of Electrical and Electronic Engineers Standards Association (IEEE-SA) and Underwriter's Laboratory (UL), DER inverters are designed, manufactured and tested to provide reliable and safe functionalities beyond the scope of conversion of DC power into an AC power waveform. Optimization of power conversion, manipulation of voltage, and grid synchronization are central to ensuring that load devices are able to consume power. Workforce and public safety is augmented through the ability to disconnect from the point of common coupling (PCC) and the implementation of unintentional islanding protection.

### 1.2.1 Power Transfer Optimization

Inverters are designed to optimize transfer of power from a DER to a load, often through a technique called Maximum Power Point Tracking (MPPT). Optimization is typically achieved through the design of an algorithm which computes the ideal equivalent resistance from measurements of current, voltage, and the respective rates of change. MPPT is subsequently implemented by an intelligent controller that makes frequent calculations and actuates corresponding adjustments. In the certification process, efficiency of an inverter is evaluated with respect to peak operation and overall performance under a range of testing conditions. Through these tests, peak efficiency is measured and an overall value is computed, using a weighting methodology such as that outlined by the California Energy Commission (CEC)[1], and both values are reported with the device specifications. Typically, inverters achieve upwards of 90% weighted power conversion efficiency, with many commercially available models reaching 97% peak efficiency or higher.

### 1.2.2 Voltage Conversion

In order to supply power to a load or to the distribution grid, power generated by a distributed energy resource usually must be delivered at a different voltage. Often, as in the case of solar photovoltaic generators, this resource's generation voltage is lower than 4 kV, the lowest primary distribution voltage in the United States. Furthermore, the voltage is typically intrinsic to the device or predictable based on input parameters, which allows for an inverter to implement consistent voltage step-up. This manipulation may be achieved through use of a transformer, an electrical device which converts voltages through inductive coupling, or through advanced power electronics-based switching circuitry.

### 1.2.3 Grid Synchronization

A central component of an inverter's efficacy is the ability to construct an output AC waveform that is synchronized with the utility distribution system. The supply of a waveform whose frequency is identical to the grid frequency represents the key requirement of the grid synchronization functions. Also, phase synchronization for each of the three phases of a three-phase interconnection is required for grid synchronization. The device's internal power electronics execute control strategies which emulate the frequency and phase of the power on the coupled network. Filtering and pulse-width modulation are incorporated as technical solutions to mitigate flicker, harmonic distortion, and other potential issues. Phase differences can cause losses and reduce voltage, while small incompatibilities in frequency alignment result in significant power loss and, over time, could cause fault conditions if not rectified.

### 1.2.4 Disconnection

When fault conditions are present, a grid-tied inverter is required to disconnect from the distribution system at the point of common coupling (PCC). IEEE 1547 outlines the unacceptable, fault-indicating values of frequency and voltage based on the magnitude and duration of the signal. If either parameter rises or falls to such an extent in response to an event, then remains at such a level for a prescribed duration of time after the event, the inverter must initiate a disconnection from the grid. This fundamental safety functionality provides a standardized level of protection from the potential impacts of a fault.

### 1.2.5 Anti-Islanding Protection

Unintentional islanding is a potentially damaging system configuration which may occur in the presence of undetected fault conditions. The formation of a localized grid is initiated by a blackout or a disconnection from the distribution network, and the entirety

[1] "Guideline for the use of the Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems" http://www.gosolarcalifornia.org/equipment/documents/Sandia_Guideline_2005.pdf

of the local load is transferred to the DERs which remain connected. Although the potential for a distribution system incorporating intentional localized grids connected to DERs, or microgrids, is a compelling technical advance especially at high levels of DER penetration, island formation carries a range of potential consequences when unintentional and without proper control strategies in place. These consequences can result from lacking capacity to satisfy the load, or from failure to operate within specified parameters like voltage and current limits. Such conditions may endanger workforce and public safety, and thus represent a critical consideration in the power engineering profession. Furthermore, unintentional islanding could have ramifications upon the devices which draw power from the islanding circuit.

Anti-islanding protection schemes are tested in accordance with IEEE 1547.1, "IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems," which prescribes a range of loading conditions and parameters that recreate islanded conditions. IEEE 1547 implements a standard requirement that disconnection must occur within two seconds of island formation. A range of different algorithms and protection schemes may be implemented, but all must pass the test procedures prescribed by IEEE 1547.1 and thereby comply with the IEEE 1547 standard. These schemes may be based on the detection of relevant parameters, including frequency and harmonic distortion, which can collectively indicate the presence of an islanding condition. An additional methodology employs the active technique of forcing a parameter such as current or frequency, inducing a relatively small change which will be observable in grid conditions only when an island has formed.

### 1.2.6 Storage Interfacing

An inverter may enable the integration of a battery or other energy storage device with a distributed generator. When active power is produced by a distributed generator, a standard inverter will route the power to the grid. If that active power is not needed, an inverter may reroute the active power to be stored. When power is again required by the grid, the storage device may be employed as a supply of power, complementing the power provided by the distributed energy resource. In the case of utility interconnected inverter, pricing signals may be employed in the future to autonomously activate the charging or discharging modes of the storage device. Energy storage represents a particularly useful capability in light of the intermittency of many forms of distributed generation, particularly those which rely on solar or wind power. It is also a capability which may lend additional profitability to the installation of distributed generators through maximizing the economic value of generated power. The adoption of present storage technology has inherent challenges surrounding cost-effectiveness and duration of life cycle, and available technologies must be evaluated on a case-by-case basis to best suit the intended application.

# 2 Overview of Advanced Inverter Functions

## 2.1 Advanced Inverter Key Concepts

A standard DER inverter will efficiently supply grid-synchronized power to a load and/or to the grid. In addition, standards require an inverter to provide fundamental safety features such as anti-islanding and fault detection. Surpassing this scope, an advanced inverter has the capacity to supply or absorb reactive power, to control and modulate frequency and voltage, and to provide more robust safety and reliability functionalities in voltage and frequency ride-through. Reactive power, measured in Volt-Amperes Reactive (VARs), is associated with inductive and capacitive loads and manifests as energy stored in magnetic or electric fields. Historically, capacitors could be installed to either supply or absorb reactive power where needed on distribution feeders to attempt to minimize reactive power from inductive loads. One limitation of using capacitors for this purpose is that there is limited variability of reactive power that can be supplied or absorbed dependent on the ability to switch on/off various combinations of capacitors at a location. In addition, reactive power supplied or absorbed by capacitors will greatly change with minor changes in voltage level. As a flexible source and sink of both active and reactive power, advanced inverters provide an opportunity for the extensive control that enables safety and reliability in DER applications.

## 2.2 Advanced Inverter Functionalities

### 2.2.1 Reactive Power Control

Definition: As described above, a DER interconnected advanced inverter has the capacity to act as a supply of reactive power. Inductive loads, such as induction motors and fluorescent lighting, are inherent to the distribution system. The presence of such loads results in a phase difference between voltage and current waveforms, causing losses which reduce the efficiency of real power distribution. Less efficient power distribution requires greater current, which magnifies the impact of line losses and of drops in the voltage profile over the distribution line. Reactive power control, or “VAR control”, in inverters provides for the intelligent supply of reactive power in response to these issues. Appropriately modulated reactive power support resolves phase differences between voltage and current, reducing distribution losses, raising voltage levels, and significantly impacting both local power quality and distribution efficiency.

Implementation: The supply of reactive power via capacitors will cause the phase of the current to lead that of the voltage, while the opposite may be achieved when an inductive load absorbs reactive power. Inductive loads are quite prevalent on the distribution network, and accordingly the grid requires capacitive supply of reactive power in most cases. Both resistive and inductive loads may be supplied, as an advanced inverter is capable of contributing active power and reactive power simultaneously. A capability curve prescribes the output reactive power, which is diminished at lower voltage levels and at higher output active power. VAR control enables the manipulation of the inverter’s power factor according to the characteristic capability curve in order to match the mix of resistive and inductive loads on the circuit. Power factor is defined as the ratio between active power supplied, measured in Watts, and the apparent power supplied, measured in Volt-Amperes and computed as the Pythagorean sum of active and reactive power. A power factor of one indicates that active power makes up the entirety of the apparent power supplied by an inverter, and that no reactive power is supplied. On the other hand, a power factor of zero occurs when an inverter supplies solely reactive power.

Adjustment of an inverter's output power factor may be performed through predefined static settings which are scheduled according to load forecasting. Manipulation may alternatively be achieved through modes which provide specific responses to grid conditions such as voltage levels. These modes incorporate such considerations as hysteresis, modulated ramp rates, and randomization of the execution time window to address potential interoperability concerns and ensure stable actuation. Modes and settings provide predictable yet flexible solutions, enabling either localized autonomous control or centralized management schemes.

Impact: The technique of reactive power control has significant potential to increase efficiency and flexibility of power distribution. When the power system dynamics of an unsupported inductive load lead to a drop in voltage levels, injecting capacitive, reactive power will resolve this voltage drop. Currently, the distribution system is outfitted with capacitors which provide reactive power support, but these devices provide support of limited resolution that is more static by nature. Integrated, controlled power electronics-based systems such as voltage regulators are also available to distribution system engineers, but these technologies tend to be expensive for providing sufficient resolution. The efficacy of reactive power control is highly dependent on geographic proximity to the load or substation that requires support due to the impact of line losses, and DER inverters are therefore a logical source of reactive power because of their distributed nature. Furthermore, the precise modulation of the power factor experienced by a load requires similarly precise modulation of reactive power supplied to the conductor and load, a definite benefit of an inverter. The integration of these capabilities within each node of the distribution system associated with a DER would provide for a more effective network of support with higher resolution and greater flexibility. This flexibility allows for a range of distribution grid management structures and control methodologies and thereby enables the resolution of potential grid issues both locally and across large distribution networks.

### 2.2.2 Voltage and Frequency Ride-Through

Definition: Ride-through may be defined as the ability of an electronic device to respond appropriately to a temporary fault in the distribution line to which the device is connected. A fault typically derives from conditions or events that are extreme or unanticipated and cause an unintended short-circuit. When a distribution circuit is shorted, part of the circuit experiences an overcurrent for the duration of the fault, which can cause resistive loads to dissipate excess power and overheat, voltage levels to fall, and utility or customer equipment to exceed operating limits and fail. As previously discussed, standard inverters are required to identify a typical fault and disconnect from the circuit when a fault is detected. Should the fault prove to be temporary or to otherwise not have an impact on the distributed energy resource connected to the inverter, this course of action will inhibit the DER's operation and prevent it from functioning under the restored normal conditions. Ride-through addresses this deficiency through monitoring and responding to fluctuations in voltage or frequency and thereby increases the reliability of a DER.

Implementation: While the current standards already require some ride through of certain times periods for certain voltage and frequency excursions, this functionality in standard inverters is fairly limited. The variety of responses instituted by a ride-through capable inverter will depend upon the type of fault condition that is sensed and the internal setting that is active. The most prevalent ride-through capabilities are tied to measurements of the distribution system's AC frequency and voltage. Most approaches to the resolution of frequency quality issues require the modulation of active power supplied, as a lower or higher frequency can result from the under- or over-supply, respectively, of active power to a circuit. On the other hand, sags and swells in voltage levels can be remedied by the injection of reactive power into the line. If the voltage is too low, the power factor can be raised through reactive power support to reduce line losses and increase voltage, while lowering the power factor can similarly resolve a voltage level swell. The implementation of these methods may be achieved through autonomous control or through predefined settings, which will cater responses that correspond to particular sets of parameters.

Ride-through functionality is highly dependent on monitoring, processing, and algorithmic response. Monitoring of frequency or voltage permits identification of an over-/under-voltage or an over-/under-frequency condition. In the event of such a condition, monitoring of the relevant parameter will continue and a response will be actuated. The controlling algorithm will implement a response, such as an increase in power in response to a low voltage, which has potential to resolve a temporary condition and to remove the need for a disconnection. If the condition persists and the inverter fails to reach sufficient parameters within the IEEE 1547 disconnection time frame, the disconnection will take place as with the standard inverter, ceasing all ride-through responses.

Impact: The voltage and frequency ride-through functionalities provide dynamic support to the grid in the presence of an observable discrepancy along the interconnected line. In responding actively to atypical conditions, ride-through executes the required disconnection in the case of an irresolvable, permanent fault, and can prevent disconnection in cases where these conditions result from temporary or isolated events. The avoidance of "unnecessary" disconnection improves grid reliability by enabling the DER to continue to supply power and support functions to the grid. A cautionary note is that there are risks associated with ride-through functionalities, especially in non-utility scale DER applications such as residential and small commercial. If ride-through is permitted by standards to prolong the presence of a fault, this could expose equipment and people using a fault circuit to greater risk of damage or injury.

# 3 National and International Inverter Standards and Related Work

## 3.1 United States Inverter Standards

Currently the main standards which govern inverters in the IEEE 1547 "Standard for Interconnecting Distributed Resources with Electric Power Systems" and UL 1741 "Standard for Safety for Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources." IEEE 1547 establishes criteria and requirements for interconnection of DER with electric power systems. IEEE 1547 purpose is to provide a uniform standard for interconnection of distributed resources with electric power systems. IEEE 1547 provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection. IEEE 1547 Standard was approved by the IEEE Standards Board in June 2003 and approved as an American National Standard in October 2003. The U.S. Energy Policy Act of 2005 established IEEE 1547 as the national standard and also called for State commissions to consider adopting standards for electric utilities. Under Section 1254 of the Act: "Interconnection services shall be offered based upon the standards developed by the Institute of Electrical and Electronics Engineers: *IEEE Standard 1547 for Interconnecting Distributed Resources with Electric Power Systems*, as they may be amended from time to time."

UL 1741 references and expands upon IEEE 1547, specifically addressing safety concerns related to grid-connected power generators, including protection against risk of injury to persons. For utmost consideration of workforce and public safety, in particular for residential and small commercial applications, both standards at this time prohibit voltage regulation by DER. Large, international inverter manufacturers tend to supply utilities with models with the ability to provide local voltage regulation, but these functions are disabled per IEEE 1547 and UL 1741. This essentially inhibits the adoption of many of the advanced functionalities of inverters. However, it should be noted that the utilities are not required to comply with UL 1741 requirements and many do not, instead adding additional protective equipment along with their inverters. However, for non-utility inverters connected to the grid, UL 1741 compliance is often a utility requirement, or in the case of California a State requirement from CEC and CPUC rules, such as the Interconnection Rule 21.

In May of 2012, an IEEE workshop was held to get industry feedback on potential changes to IEEE 1547 and subsequently IEEE embarked on an initiative to look into amending the standard to address the following topics: 1) voltage regulation; 2) voltage ride-through; and 3) frequency ride-through.[2] Currently, there is are several working groups that are developing several amendments to the IEEE 1547 standard, which CPUC staff monitors for any issues that may impact State policy. The related UL 1741 standard will also needs to be updated to correspond to the eventual IEEE 1547 amendments.

## 3.2 International Inverter Standards

Other countries around the world, particularly in Europe, have similar standards governing aspects of their power distribution systems. Some representative examples are *Journal Officiel de la République Française* DEVE0808815A of France, *Real Decreto* 661/2007 of Spain, the Italian *Comitato Elettrotecnico Italiano* 0-21, and the BDEW Medium Voltage Guideline, “Generating Plants Connected to the Medium Voltage Network” from Germany. The European Low Voltage Directive, which provides some form of standardization across national borders, is superseded by the respective regulations. Though each of these national standards is distinct and minimally

[2] http://grouper.ieee.org/groups/scc21/1547/1547_index.html

standardized at an international level, each provides a technical treatment of reactive power and voltage regulation. Also of note, the German standard implements requirements surrounding dynamic network fault support, which includes the ride-through functionalities. These European standards also require some level of communication, monitoring and control between the DER inverters and/or controllers and the utilities' distribution grid management systems.

## 3.3 Photovoltaic Inverters Compliance Requirements in California

The CEC, as dictated by California legislation, SB 1 (2006), maintains an extensive list of UL 1741-compliant photovoltaic inverter models as verified by a Nationally Recognized Testing Laboratory (NRTL). This compliance is required for qualification for the California Solar Initiative (CSI) rebate program, an economic incentive through which the State may shape the technology adopted by consumers in a portion of the inverter market. The spectrum of inverters which meet these standards includes a diverse blend of models at a variety of nominal output power capacities. Table 1 includes a sampling of some of the larger inverters on the CEC's "List of Eligible Solar Inverters per SB 1 Guidelines.[3]" The two additional parameters that the CEC reports are weighted efficiency and whether or not there is an approved built-in meter. Most of these models at this scale are for three-phase (3-Φ) utility interactive inverters. Utility-Interactive Inverter (UII) is defined in the National Electric Code as "an inverter intended for use in parallel with an electric utility to supply common loads that may deliver power to a utility." The term grid-tied inverter is often used synonymously with the NEC's UII within the industry.

**Table 1 – Sampling from CEC List of Eligible Solar Inverters per SB 1 Guidelines**

| Manufacturer Name | Inverter Model No. | Description | Power Rating (Watts) | Weighted Efficiency | Approved Built-In Meter |
|---|---|---|---|---|---|
| Advanced Energy Industries | Solaron 500kW | 500kW 480Vac Three-Phase (3- ϕ) Utility Interactive Inverter | 500000 | 97.5 | No |
| American Electric Technologies | ISIS-1000-15000-60-CG | 1000kW 3-ϕ UII | 1000000 | 96.5 | No |
| Chint Power Systems America | CPS SC100KT-O/xx-480 | 100kW (480Vac) UII w/ dual inputs | 100000 | 96 | Yes |
| Diehl AKO Stiftung & Co. KG | Platinum 100 CS-A HE 480 | 100kW 480Vac 3-ϕ UII | 100000 | 95.5 | Yes |
| Eaton | S-Max 250kW (600V) | S-Max™ Series 250kW 600 Vac 3-ϕ UII 300-600 Vdc input | 250000 | 96 | Yes |
| Green Power Technologies | PV500U | 500 kW 3-ϕ, UII w/ Med Voltage TP1 Xfmr | 500000 | 96 | Yes |
| Ingeteam Energy S.A. | INGECON SUN 220 TL U 360 Outdoor | 220kW 360Vac 3-ϕ UII | 220000 | 97.5 | Yes |
| KACO | XP100U-H4 | 100 kW 480Vac 3-ϕ UII | 100000 | 96 | Yes |

[3] "List of Eligible Solar Inverters per SB 1 Guidelines" http://www.gosolarcalifornia.org/equipment/inverters.php

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|---|---|---|---|---|---|
| Princeton Power Systems | GTIB-480-100-xxxx | 100 kW, 480Vac, UII (600Vdc Max) | 100000 | 95 | No |
| PV Powered | PVP260KW | 260kW (480Vac) 3-ϕ UII 2/ 295-600Vdc input | 260000 | 97 | Yes |
| SatCon Technology | PVS-1000 (MVT) | 1000 kW 3-ϕ Inverter for Med Voltage Xfmr | 1000000 | 96 | Yes |
| Shenzhen BYD | BSG250K-U or U/N | 250kW UII | 250000 | 95 | No |
| Siemens Industry | SINVERT PVS1401 UL | 1400 kW 480 Vac 3-ϕ Inverter (Master Unit, 3 Slave Units) | 1400000 | 96 | Yes |
| SMA America | SC800CP-US | 800 kW 3-phase, UII w/ Medium Voltage ABB Xfmr | 800000 | 97.5 | Yes |
| Solectria Renewables | SGI 500-480 | 500kW 480Vac Utility Scale Grid-Tied Smartgrid PV Inverter | 500000 | 97 | Yes |
| Sungrow Power Supply | SG500LV | 500kW UII to connect w/ med voltage xfmr | 500000 | 96.5 | Yes |
| TMEIC | PVL-L0500U | 500kW UII for medium voltage xfmr | 500000 | 95.5 | Yes |
| Toshiba | PVL-L0500U | 500kW UII for medium voltage xfmr | 500000 | 95.5 | Yes |
| Xantrex Technology (Schneider Electric) | GT500-MVX | 500kW 3-ϕ Inverter for Medium Voltage Applications | 500000 | 95.5 | Yes |

## 3.4 Advanced Inverter Availability Comparison

This representative study presents a comparison between central photovoltaic inverter models compliant with United States standards and those compliant with European standards. This analysis examines two 500 kV nominal output power models from each of three international inverter manufacturers: Schneider Electric, SatCon, and SMA. Among utility scale central inverters such as those presented, functionalities and capabilities are fairly uniform across manufacturers, and these three were selected as samples. Central inverter models were chosen because advanced functionalities are supported to the largest extent in utility-scale applications.

The two models from each manufacturer retain extremely similar profiles, but are distinct in a number of features. The central point of differentiation, which is shared among at least two of the three manufacturer's models, is reflected in the relevant standards: the U.S. models meet United States standards UL 1741 and IEEE 1547, while the European models all comply with EU requirements and German BDEW requirements. As a result, there may be fundamental differences between nominally similar models. These distinctions are relevant because a utility must install additional protection in lieu of a UL certification, and thus UL-certified models are preferable.

The Schneider Electric GT500E (Europe) specification optionally includes "grid interactive features including low voltage ride through and reactive power control", an option which is not listed under the options for the GT500 (United States). The SatCon models follow suit, as the 500 kW PowerGate Plus_CE (Europe) model provides “remote control of real and reactive power”, “low-voltage ride through”, and “power factor control.” The 500 kW PowerGate Plus (United States) is only capable of providing two of the three functions, as the “Advanced Power Modes” allow supply of real and reactive power under either “Constant VAR” or “Constant Power Factor” settings.

Text from recent SMA inverter specification sheets is similar for the Sunny Central 500CP (Europe) and Sunny Central 500CP-US (United States), as they both describe “Powerful grid management functions (including Low Voltage Ride Through and Frequency Ride Through)”. Older U.S. models including the Sunny Central 500HE-US specifications make no mention of such capabilities while the European compliant HE model does mention those same advanced capabilities, reflecting a chronological progression into these advanced capabilities.

From a limited amount of investigation, it appears that the majority of models which comply with UL 1741 and which are on the market do provide some advanced inverter functionalities, albeit with some caveats. As gleaned from conversations with inverter manufacturers, the primary reason is that UL 1741 prohibits intentional islanding and low-voltage ride through. Manufacturers and California utilities both indicate that U.S. utilities tend to purchase inverters with these advanced functionalities, as they do not have to be in compliance with UL standards and instead may add additional protective equipment along with their inverters. A manufacturer representative further stated that big photovoltaic power plants tend to want to be declared utilities or independent power producers so that they can also avoid compliance with UL standards.

This exercise reveals a clear discrepancy between the intended usage of inverter models which are manufactured for use in Europe and those manufactured for use in the United States, even within individual manufacturers. Though manufacturer representatives have stated that the hardware of their UL- and EU-certified models is frequently equivalent or similar, the software will constrain the functionalities of the UL-certified models. These advanced functionalities, which have been deployed in countries such as Germany and Italy, are not permissible under current U.S. standards, and as such are disabled in installed inverters with these advanced capabilities are not currently in use by non-utilities or independent power producers in the United States.

## 3.5 Other Related National & International Standards Development Work

Since 2009, EPRI has been facilitating an industry collaborative initiative that is working to define common functions and communication protocols for integration of smart distributed resources with the grid. The goal is to enable high-penetration scenarios in which a diversity of resources (for example, photovoltaic and battery storage) in varying sizes and from varying manufacturers can be integrated into distribution circuits in a manageable and beneficial way. This requires a degree of consistency in the services and functions that these devices provide and uniform, standards-based communication protocols for their integration with utility distribution management and supervisory control and data acquisition (SCADA) systems.

The EPRI initiative has engaged a large number of individuals representing inverter manufacturers, system integrators, utilities, universities, and research organizations. The resulting work products have provided valuable input to a number of standards organizations and activities, including the National Institute of Standards and Technology (NIST) and the International Electrotechnical Commission (IEC). Participation in this activity has been, and remains, open to anyone who is interested. Volunteers met by teleconference throughout 2010 and 2011, discussing, defining and documenting proposed common functions. EPRI's report "Common Functions of Smart Inverters" provides a compiled summary of the function descriptions that this initiative has produced thus far. Each function is presented in the form of a proposal, which is the language used by the volunteer working group. This reflects the fact that the functions are not legal standards unless and until they are adopted by a standards development organization (SDO).

EPRI encourages utilities and device manufacturers to utilize these functional descriptions to aid in the development of requirements for smart distributed resources. Even more beneficial may be the referencing of open standards that have been derived from this work, such as Distributed Network Protocol (DNP3) mapping. The process of developing a complete design specification for a smart photovoltaic, battery-storage, or other inverter-based system may be greatly simplified by taking advantage of this body of collaborative industry work. While it is always possible to independently craft new functions, or to design similar functions that work in slightly different ways, such effort does not bring the industry closer to the end-goal of off-the-shelf interoperability and ease of system integration.

# 4 Impacts & Challenges of Advanced Inverters Widespread Adoption

4.1 Impacts: The widespread integration of DERs into the power distribution network presents a number of technical challenges which advanced inverter functionalities could help mitigate. At its core, reactive power control increases efficiency of power distribution by reducing line losses. The efficacy of VAR control is highly dependent on geographic proximity to the line or feeder that requires support, and DER inverters are therefore a logical source of reactive power. The power quality benefits may be implemented statically, through scheduling, or dynamically, using predefined settings and modes. This flexibility allows for a range of distribution grid management structures and control methodologies and thereby enables the resolution of potential grid issues both locally and across large distribution networks. The voltage and frequency ride-through functionalities provide dynamic grid support in the presence of a fault along the interconnected line. In responding actively to atypical conditions, ride-through can prevent disconnection in cases where these conditions result from temporary or isolated events. Avoiding "unnecessary" disconnection, especially of large distributed energy resources, could improve grid reliability.

4.2 Challenges: One of the largest challenges in the industry in the United States is the fact that many inverters being deployed are not owned, operated, managed and controlled by distribution utility companies. In addition, there is ongoing work to develop interoperability standards for DER devices including inverters and inverter controllers so that DER management systems can be developed and integrated with utility distribution management systems. However, at this point in time, there is a lack of consistent standards in the U.S. that will allow various entities to exchange critical inverter data to a distribution management system and integrate that into a utility DMS. Without this ability, there will be limitations to how much these advanced functionalities can be used autonomously without adversely impacting the grid or other customers' equipment. Finally, power quality may be another challenge with more use of inverters producing current harmonics which then emanate onto the grid.

Another challenge is the fact that safety and performance requirements are combined in U.S. standards for inverters (i.e. IEEE 1547 and UL 1741). This could become more of an issue in the future if safety requirements distinguish between residential and small commercial applications versus large DER power plants or storage facilities. There is an argument to be made for the implementation of different safety requirements and standards for residential and small commercial applications. In terms of public and workforce safety, in residential and small commercial applications it could be more important for compliance standards to be more cautious and lean towards requiring disconnection of the DER. On the other hand, for large power plants that are being relied upon for generation, it might be better to lean towards keeping them connected to support the grid. The latter requirements would also need to include other grid protective devices to provide workforce and public protection.

To highlight the importance of inverter functionality, EPRI conducted a study indicating that over 69% of downtime events are caused by the PV inverters[4]. The main contributors to these failures were software bugs and material failures, which indicates a need for significant refining of the inverter technologies being deployed. The EPRI report further notes the lack of "complete performance criteria" for the implementation and use of these inverters, a tool that would assist in providing a smoother transition to high levels of penetration.

# 5 Conclusion

Advanced inverter functionalities may lend significant improvement to the stability, reliability, and efficiency, of the electric power distribution system in the US. Distribution automation systems implemented by utilities will be central to the integration of these functionalities, which require protection, control, and communication to reach full efficacy. Implementation of reactive power support functions can permit DER to respond to loading conditions to minimize losses and improve the quality of supplied power. By the same token, ride-through of adverse voltage and frequency conditions may enable inverter response to mitigate the impact of unexpected conditions, maintain interconnection, and thereby lend resiliency to these resources. At present, US compliance-based standards for interoperability and performance tend to inhibit the

[4] EPRI: "Utility Scale Photovoltaic Inverters" (2011)

implementation of these functionalities, but they are being revised to consider safe and reliable augmentation of inverter functionality to support increased penetration of DER.

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