Advanced Inverter Technologies

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Wendy al-Mukdad, PE
Grid Planning & Reliability
Energy Division
California Public Utilities Commission

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Staff Report's Main Topics

1. Technical Background on Inverters
   1. Standard Inverter Key Concepts
   2. Standard Inverter Functionalities
2. Overview of Advanced Inverter Functions
   1. Advanced Inverter Key Concepts
   2. Advanced Inverter Functionalities
      - Reactive Power Control
      - Voltage and Frequency Ride-Through
3. National and International Standards & Related Work
   1. United States Inverter Standards
   2. International Inverter Standards
   3. Photovoltaic Inverters Compliance Requirements in California
   4. Advanced Inverter Availability Comparison
   5. Other Related National & International Standards Development
4. Impacts & Challenges of Advanced Inverters Widespread Adoption

Standard Inverter Key Concepts

- Inverter is a device which converts DC input to 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 distributions 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.

Standard Inverter Functionalities

- In compliance with standards developed by SDOs such as IEEE-SA and 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.
- Specific standard functionalities identified and described in report:
    1. Power Transfer Optimization
    2. Voltage Conversion
    3. Grid Synchronization
    4. Disconnection
    5. Anti-Islanding Protection
    6. Storage Interfacing

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 (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.

Reactive Power Control Implementation

- 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 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 (PF) according to the characteristic capability curve in order to match the mix of resistive and inductive loads on the circuit.
- Adjustment of an inverter's output PF may be performed through predefined static setttings 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 CENTRAL MANAGEMENT SCHEMES.

Reactive Power Control 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 PF 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.**

Voltage and Frequency Ride-Through Implementation

- While the current standards already require some ride through of certain time periods for certain voltages 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 PF can be raised through reactive power support to reduce line losses and increase voltage, while lowering the PF 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.**

Voltage and Frequency Ride-Through 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 to greater risk of damage or injury (or death).

US Inverter Standards – IEEE 1547

- 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 (EPS).
- 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."

US Inverter Standards – UL 1741

- 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.
- For nonutility 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.

US Inverter Standards – IEEE 1547A & UL 1741 Update

- 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;
    3) frequency ride-through.
- Currently, there are several working groups that are developing several amendments to the IEEE 1547 standard.
- The related UL 1741 standard will also needs to be updated to correspond to the eventual IEEE 1547 amendments.
- One important distinction in understanding the IEEE 1547 standards is that only IEEE 1547 and 1547.1 are compliance standards (i.e. use language such as ‘shall’).
- The other IEEE 1547 standards are either recommendations or guidelines (i.e. use language such as ‘should’ or ‘may’).
- Please note that it is staff’s current understanding that most IEEE 1547 working group volunteers are focusing on IEEE 1547A since it is a fast-track amendment and will be a compliance standard.

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 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.**

Photovoltaic Inverters Compliance Requirements in CA

- 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."
- 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 SB1 Guidelines (Note: UII = Utility Interactive Inverter)

Manufacturer Name	Inverter Model No.	Description	Power Rating (Watts)	Weighted Efficiency	Approved Built-in Meter
Advanced Energy Industries	Solaron 500kW	500kW 480Vac 3-Φ UII	500000	97.5	No
American Electric Technologies	ISIS-1000-15000-60-CG	1000kW 3-Φ UII	1000000	96.5	No
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
KACO	XP100U-H4	100kW 480Vac 3-Φ UII	100000	96	Yes
Princeton Power Systems	GTIB-480-100-xxxx	100kW, 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

Table 1 – Sampling from CEC List of Eligible Solar Inverters per SB1 Guidelines (cont'd)

Manufacturer Name	Inverter Model No.	Description	Power Rating (Watts)	Weighted Efficiency	Approved Built-in Meter
Shenzhen BYD	PSG250K-U or U/N	250kW UII	250000	95	No
Siemens Industry	SINVERT PVS1401 UL	1400kW 480 Vac 3-Φ Inverter (Master Unit, 3 Slave Units)	1400000	96	Yes
SMA America	SC800CP-US	800kW 3-Φ, UII w/ Med Voltage ABB Xfmr	800000	97.5	Yes
Solectria Renewables	SGI 500-480	500kW 480Vac Utility Scale Grid-Tied SG PV Inverter	500000	97	Yes
Toshiba	PVL-L0500U	500kW UII for med voltage xfmr	500000	95.5	Yes
Xantrex Technology (Schneider Electric)	GT500-MVX	500kW 3-Φ Inverter for Med Voltage Applications	500000	95.5	Yes

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

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.**

Advanced Inverter Availability Comparison (2)

- As a result of different compliance standards in the US and Europe, 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 10 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)”.

Advanced Inverter Availability Comparison (3)

- 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 understood from conversations with industry experts, 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.

Advanced Inverter Availability Comparison (4)

- This analysis 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.**
- **As such, these advanced functionalities are disabled in installed inverters with these advanced capabilities and are not currently in use by non-utilities or independent power producers in the United States.**

Other Related National & Int'l Stds 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).

Other Related National & Int’l Stds Dev Work (2)

- 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 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 smart distributed resources requirements.
- **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.

Impacts of Advanced Inverters Widespread Adoption

- 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.

Challenges of Advanced Inverters Widespread Adoption

- 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.

Challenges of Advanced Inverters Widespread Adoption (2)

- 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.

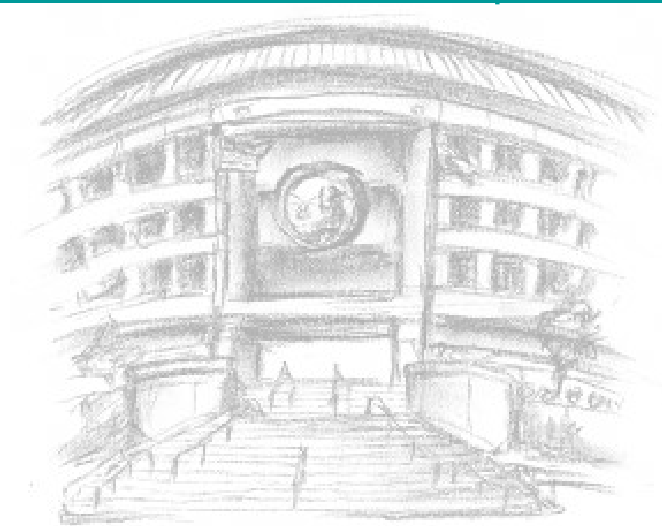
Staff Report Conclusion

- Advanced inverter functionalities may lend significant improvement to the stability, reliability, and efficiency, of the electric power distribution system in the United States.
- 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 implementation of these functionalities, but they are being revised to consider safe and reliable augmentation of inverter functionality to support increased penetration of DER.

Thank you!

Staff Report is available at CPUC website:

http://www.cpuc.ca.gov/NR/rdonlyres/6B8A077D-ABA8-449B-8DD4-CA5E3428D459/0/CPUCAdvancedInverterReport2013FINAL.pdf



For further information please contact Wendy Al-Mukdad:

Phone: 415-703-2311

E-mail: Wendy.al-Mukdad@cpuc.ca.gov