Cautionary Note!!!

The staff report and this updated presentation is a work-in-progress as additional professional peer review is being sought by numerous other subject matter experts, utilities engineers, and standards committee members. Please feel free to provide your professional input, preferably in writing, to me, too.
Staff Report’s Main Topics with Some Updates

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
   • United States Inverter Standards
   • International Inverter Standards
   • Photovoltaic Inverters Compliance Requirements in California
   • Advanced Inverter Availability Comparison
   • Other Related National & International Standards Development

4. Impacts & Challenges of Advanced Inverters Widespread Adoption

5. CPUC Smart Inverter Functionalities Workshop (R.11-09-011)
Standard Inverter Key Concepts

• Inverter is a device which converts DC power to AC power.
• Inverters are used in a range of applications including:
  – consumer power electronics
  – electric vehicles
  – photovoltaic and energy storage interconnections
• Inverters may stand alone and supply generated power solely to connected loads (i.e. off-grid).
• 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 generating device and improving response to power demands.
Standard Inverter Functionalities

• In compliance with standards developed by Standard Development Organizations (SDOs), Distributed Energy Resource (DER) inverters are designed, manufactured and tested to provide reliable and safe functionalities.

• Optimization of power conversion, grid synchronization and manipulation of voltage are central to ensuring that load devices are able to consume power.

• Workforce and public safety is augmented through fault detection, the ability to disconnect from the point of common coupling (PCC) and the implementation of unintentional islanding protection.
Standard Inverter Functionalities

- 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

- Advanced inverters have the capacity to supply or absorb reactive power, and to control and modulate frequency and voltage.
- Presently, capacitors and voltage regulators are installed to offset reactive power produced by inductive loads on distribution feeders.
- One limitation of using capacitors for this purpose is that there is limited variability of reactive power that can be supplied as it is dependent on the ability to switch on/off various combinations of capacitors at a location.
- In addition, reactive power supplied 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

• VAR control enables the manipulation of the inverter’s power factor (PF) according to the characteristic capability curve.

• Adjustment of an inverter’s output PF 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.

• Modes and settings provide predictable yet flexible solutions, enabling either localized autonomous control or central management schemes.

• When power system dynamics of an unsupported inductive load lead to a drop in voltage levels, injecting capacitive, reactive power may resolve this voltage drop.
Reactive Power Control Impact

• 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.

• 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.
Voltage and Frequency Ride-Through Implementation

• While current compliance standards already require some ride through of certain time periods for certain voltages and frequency excursions, this functionality in standard inverters is fairly limited in the United States.

• 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 voltage.

• If the voltage is too low, the power factor (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 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 to prolong the presence of a fault, this could expose equipment and people to greater risk of damage or injury (or even death).
US Inverter Standards – IEEE 1547 (1)

• 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."

• In IEEE Std 1547 Abstract, it states IEEE 1547 has the potential to be used in federal legislation and rule making and state public utilities commission (PUC) deliberations and by over 3000 utilities in formulating technical requirements for interconnection agreements for distributed generators powering the electric grid.
IEEE 1547 focuses on the technical specifications for, and testing of, the interconnection itself. It provides requirements relevant to the performance, operation, testing, safety considerations, and maintenance of the interconnection.

It includes general requirements, response to abnormal conditions, power quality, islanding, and test specifications and requirements for design, production, installation evaluation, commissioning, and periodic tests.

The stated requirements are universally needed for interconnection of distributed resources (DR), including synchronous machines, induction machines, or power inverters/converters and will be sufficient for most installations.

The criteria and requirements are applicable to all DR technologies, with aggregate capacity of 10 MVA or less at the point of common coupling, interconnected to electric power systems at typical primary and/or secondary distribution voltages.

Installation of DR on radial primary and secondary distribution systems is the main emphasis of this document, although installation of DR on primary and secondary network distribution systems is considered.

This standard is written considering that the DR is a 60 Hz source.
US Inverter Standards including 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.
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.

The related 1547.1 (Conformance Test Procedures) and UL 1741 standard will also need to be updated to correspond to the final IEEE 1547A.

Currently, there is also a separate P1547.8 working group for a Recommended Practice for Establishing Methods & Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE Standard 1547.

One important distinction in understanding the IEEE 1547 standards is that only IEEE 1547 and 1547.1 are compliance standards. The other IEEE 1547 standards are either recommendations or guidelines.

Please note staff has been informed by NREL recently that a new IEEE 1547 working group will be formed soon and will have it’s first meeting in San Francisco this fall. *** OPEN TO ALL & CAN GET PDUs***
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)

<table>
<thead>
<tr>
<th>Manufacturer Name</th>
<th>Inverter Model No.</th>
<th>Description</th>
<th>Power Rating (Watts)</th>
<th>Weighted Efficiency</th>
<th>Approved Built-in Meter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced Energy Industries</td>
<td>Solaron 500kW</td>
<td>500kW 480Vac 3-Φ UII</td>
<td>500000</td>
<td>97.5</td>
<td>No</td>
</tr>
<tr>
<td>American Electric Technologies</td>
<td>ISIS-1000-15000-60-CG</td>
<td>1000kW 3-Φ UII</td>
<td>1000000</td>
<td>96.5</td>
<td>No</td>
</tr>
<tr>
<td>Eaton</td>
<td>S-Max 250kW (600V)</td>
<td>S-Max™ Series 250kW 600 Vac 3-φ UII 300-600 Vdc input</td>
<td>250000</td>
<td>96</td>
<td>Yes</td>
</tr>
<tr>
<td>Green Power Technologies</td>
<td>PV500U</td>
<td>500 kW 3-Φ, UII w/ Med Voltage TP1 Xfmr</td>
<td>500000</td>
<td>96</td>
<td>Yes</td>
</tr>
<tr>
<td>KACO</td>
<td>XP100U-H4</td>
<td>100kW 480Vac 3-Φ UII</td>
<td>100000</td>
<td>96</td>
<td>Yes</td>
</tr>
<tr>
<td>Princeton Power Systems</td>
<td>GTIB-480-100-xxxx</td>
<td>100kW, 480Vac, UII (600Vdc Max)</td>
<td>100000</td>
<td>95</td>
<td>No</td>
</tr>
<tr>
<td>PV Powered</td>
<td>PVP260kW</td>
<td>260kW (480Vac) 3-Φ UII 2/295-600Vdc input</td>
<td>260000</td>
<td>97</td>
<td>Yes</td>
</tr>
<tr>
<td>SatCon Technology</td>
<td>PVS-1000 (MVT)</td>
<td>1000 kW 3-Φ Inverter for Med Voltage Xfmr</td>
<td>1000000</td>
<td>96</td>
<td>Yes</td>
</tr>
</tbody>
</table>
## Table 1 – Sampling from CEC List of Eligible Solar Inverters per SB1 Guidelines (cont’d)

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

[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.
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 most distribution utility companies do not have the capability to communicate, monitor and control many inverters being deployed.
• In addition, there is ongoing work to develop interoperability standards for DER devices including inverters and inverter controllers or other intelligent / power-electronic based devices 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 or other power 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.
• 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

- With higher penetrations of renewable energy, advanced inverter functionalities may lend significant improvement to the stability, reliability, and efficiency, of the electric power distribution system.
- 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.
CPUC Smart Inverter Functionalities Workshop (R.11-09-011)

• June 21, 2013, 9:15am to 4pm
• CPUC Auditorium, 505 Van Ness Ave, SF
• Video Webcast or Conference Call available.
• This workshop will discuss the first phase of a smart inverter implementation plan that recommends smart inverter capabilities that could be required to ensure that long-term safety, reliability, and efficiency of the power grid with high penetration distributed generation.
• Workshop discussions will cover smart inverter functionality recommendations and a proposed testing and implementation plan for validating the recommended functions among other topics. Parties will have a chance to discuss the proposals in depth.
• Comments to the Working Group proposals and replies are due July 31, 2013 and Reply Comments are due on August 30, 2013.
• See our website for more info: http://www.cpuc.ca.gov/PUC/energy/June_21_2013_Smart_Inverter_Functionalities_Workshop.htm
Thank you!

Staff Report is available at CPUC website:

http://www.cpuc.ca.gov/NR/rdonlyres/6B8A077D-ABA8-449B-8DD4-CA5E3428D459/0/CPUCAAdvancedInverterReport2013FINAL.pdf

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