# ADVANCED INVERTER FUNCTIONS TO SUPPORT HIGH LEVELS OF DISTRIBUTED SOLAR

## POLICY AND REGULATORY CONSIDERATIONS

The use of advanced inverters in the design of solar photovoltaic (PV) systems can address some of the challenges to the integration of high levels of distributed solar generation on the electricity system. Although the term "advanced inverters" seems to imply a special type of inverter, some of the inverters currently deployed with PV systems can already provide advanced functionality, needing only software upgrades or adjustments to operation parameters. Advanced inverter functions allow for more elaborate monitoring and communication of the grid status, the ability to receive operation instructions from a centralized location, and the capability to make autonomous decisions to improve grid stability, support power quality, and provide ancillary services. The use of advanced inverter functions, and their role in maintaining grid stability, is likely to grow with increasing deployment of distributed solar and the formulation of supporting regulation and policy. But before advanced inverters can be implemented widely, various regulatory and policy issues need to be addressed, including compensation to generators for grid services provided, requirements for availability of grid services by inverter-based systems, system disconnect and operation standards, and inverter ownership structures.

This paper presents an explanation of grid integration challenges posed by increasing levels of distributed solar and a description of how advanced inverter functionalities address these challenges. It concludes with an overview of the policy and regulatory considerations that relate to the deployment of advanced inverters.

## THE NEED FOR ADVANCED INVERTER FUNCTIONS

Distributed solar capacity is increasing rapidly as technologies advance, prices decline, markets shift, and supportive policies are implemented. With the increased deployment of distributed energy resources, the electrical system is evolving from a unidirectional network, with generation flowing to customers from a few centralized generators, to a multidirectional infrastructure with generators of many sizes, on every level of the grid. Electricity system standards and operating protocols were originally designed for a dispatchable generation fleet, but today's distributed solar systems provide mostly variable, nondispatchable power.

The electricity system is evolving rapidly as a result of technological advances, market shifts, and policy changes that support increasing levels of distributed solar. Annual distributed solar capacity additions in the residential and commercial sectors are expected to rise from 3.0 GW in 2014 to 5.5 GW in 2023 (Gauntlett and Lawrence 2014). With increasing growth, system operators face new challenges to integrating distributed PV into the distribution network and bulk power system.

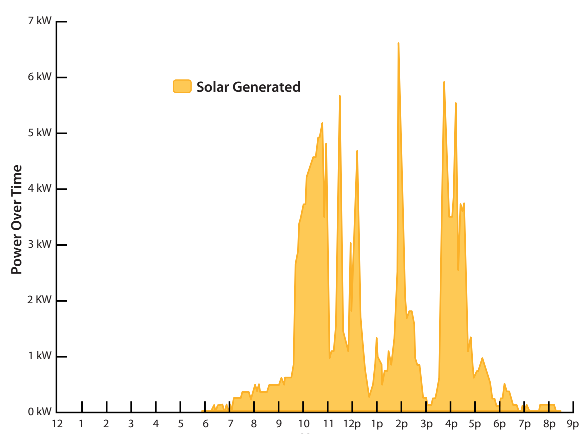


Figure 1. The Variable Generation of a Single Solar PV System. In most cases, the variability of a single system is balanced out by other systems in the vicinity.

Figure 1 shows an example of the output of a 7 kW residential solar system over the course of one day. When clouds shade the solar panels, system output drops sharply, only to spike again after cloud cover moves away.

The voltage and frequency levels of the electricity system are impacted when any type of generation is brought on-line or taken off-line. Electricity system operators must maintain a constant frequency and voltage on the system, within a specified range. Voltage and frequency disturbances pose a risk to system stability. While the grid may not be adversely impacted by the small degree of variability resulting from a few distributed PV systems, high levels of variability within a limited area may make it difficult to keep frequency and voltage levels within specified ranges. In most cases, however, PV systems are spread across a broad area such that the variability caused by localized cloud cover is balanced out across the wider system (Wiemken et al. 2001; Lew et al. 2013).

In accordance with IEEE Standard 1547, all inverters associated with distributed PV systems continuously monitor the grid for voltage and frequency levels. The PV-grid interconnection standards currently adopted by many authorities having jurisdiction (AHJs) require that PV systems disconnect when a voltage or frequency grid abnormality exceeds predetermined levels for predetermined times (IEEE 2003; IEEE 2014). If many PV systems detect a voltage disturbance and disconnect simultaneously, a sharp reduction in generation may occur, which may further exacerbate the voltage disturbance. After an outage, many solar systems ramping up simultaneously may also induce grid disturbances. To address this possibility, recent adjustments to IEEE standards now allow some flexibility in disconnection and ramp up timing (IEEE 2014).

## ADVANCED INVERTER FUNCTIONS

Advanced inverter functions can help address the grid stability problems posed by high levels of variable distributed generation. Some of these functions are described below. The inverters used today may be capable of providing some of these advanced functions with only software and operations protocol updates.

As mentioned above, current standards require that inverters disconnect the distributed PV system when grid frequency or voltage falls outside a specified range. However, inverters have the capability of "riding through" minor disturbances to frequency or voltage. These functions are called **under/over frequency ride-through** and **under/over voltage ride-through.** They direct the distributed system to stay online and respond accordingly to relatively short-term, minor events. In some cases, this function can actually help the grid to self-heal from a disturbance. Even when the ride-through functions are activated, the inverter disconnects the solar system when more severe grid disturbances warrant doing so (Beach 2003; ACEG 2014; CPUC 2014).

One way that inverters can help the grid regain stability during an under- or over-voltage event is by controlling the real and reactive power output of the distributed generation system (ACEG 2014). Voltage control is traditionally the responsibility of utilities. However, inverters can assist by changing the level of real power output from the system (**limit active power**) by controlling the rate at which real power is fed onto the grid **(controlled active power ramping),** or by injecting or absorbing reactive power into or from the grid (**reactive power compensation**, or **dynamic reactive power control**). These functions make system stability maintenance easier by keeping voltage and frequency within specified limits. While these functions currently must be set within the inverter manually, it is conceivable that they may one day be set remotely. For more information on the reactive power compensation function, see Text Box 1.

Advanced inverter functions can also help prevent the reoccurrence of a grid disturbance immediately after an outage. If many distributed generation systems come back online simultaneously, another grid disturbance may be triggered. To prevent this from happening, system operators can use a **soft start method**, which involves staggering the timing of reconnection of distributed systems on a single distribution circuit. This technique avoids spikes in the active power being fed onto the grid as it returns to normal functioning, limiting the risk of triggering another grid disturbance.

### Text Box 1: Options for Providing Reactive Power Compensation with Advanced Inverter Functionality

The provision of reactive power compensation by distributed systems can help with the integration of variable resources, contribute to grid stability, and provide system-wide cost and performance efficiencies (Kueck et al. 2008). Inverters can provide reactive power compensation when the full inverter capacity is not being used to convert active power from the solar panels. The majority of distributed solar systems have inverters that are sized in accordance with the maximum capacity of the solar panels. However, over 95% of the time, an inverter is working below its maximum current rating because the solar system is not receiving peak irradiance (Zuercher-Martinson 2012). During these times, the excess capacity can be used to provide reactive power compensation.

During peak irradiance periods, the inverter has no excess capacity. If the inverter is required to produce reactive power during these circumstances, it must do so by curtailing some of the active power from the solar panels to free up inverter capacity. **Curtailing active power generation** is an economic loss to the solar generator, which affects the overall economic viability of the solar system. While there may be clear advantages to limiting solar power output from the grid operator's perspective, those adjustments have a cost for PV system owners, who are compensated per unit of energy fed into the grid. As such, providing reactive power compensation would not be in the PV owner's economic interest, unless they were paid for this service.

One way to avoid the need to curtail for purposes of reactive power compensation is to **oversize the inverter**. Oversizing ensures that there will always be excess inverter capacity to meet voltage control needs. However, installing an inverter with a higher rating adds cost to a distributed generation system, which can be a barrier, especially for small distributed generators. Again, if generators are paid for the grid services they provide, the additional cost of oversizing an inverter may not present an economic barrier.

In locations where it is relatively expensive for a utility to provide traditional, centralized reactive power compensation, or where upgrades to equipment may become necessary, the grid services provided by advanced inverters may be assigned a higher value. In locations that have relatively poor or variable solar resource quality, advanced inverters (coupled with appropriate standards) may be able to provide reactive power compensation for a higher percentage of the time. Incentivizing system owners for reactive power compensation, in addition to the active power output of their system, would increase the economic viability of distributed solar in these locations.

Providing distributed voltage control through the reactive power compensation ability of inverters can provide cost and performance efficiencies from a system-level perspective (Kueck et al. 2008). One concern with enabling the voltage control function is that it may affect the inverter's ability to provide **unintentional-islanding protection**, which disconnects the system during a grid outage. This prevents feeding PV power onto a grid that is otherwise de-energized. PV systems powering a de-energized grid could present a risk to people and equipment. There are methods to resolve the potential interference of voltage control operations with unintentional-islanding protection, and research is continuing in this area (Beach 2013; CPUC 2014).

Until recently, U.S. standards largely prevented inverters from using their under/over frequency and voltage ride-through functions or provide voltage regulation support functions, instead requiring that distributed systems disconnect at predetermined levels of grid disturbances (IEEE Standard 1547 2003; IEEE Standard 1547a 2014).

The advanced functions described above could feasibly react either autonomously or to signals communicated by system operators. There are notable benefits to establishing **communications** between inverters and facility management systems, grid operators, and regional transmission organizations or independent system operators. Today, advanced inverters are able to receive commands to improve stability, react appropriately during emergencies, or respond to market pricing signals.

## REGULATORY AND POLICY CONSIDERATIONS FOR THE DEPLOYMENT OF ADVANCED INVERTERS

Decision makers are presented with several opportunities to enable the use of advanced inverter functions, to contribute to grid stability, and to support increased deployment of distributed solar technology. These opportunities include: requiring or encouraging inverter owners to provide grid services through regulation or compensation, ensuring that standards allow for the full use of advanced functionalities, and considering alternative ownership structures to support wide-spread adoption. Each of these opportunities is described below.

## Text Box 2: Smoothing the "Duck Curve"

The electricity that a utility must supply to meet customer demand follows a typical pattern over the course of a day, and is depicted by an electricity demand curve, also referred to as the load curve. The demand for electricity increases in the early morning hours, peaks in the late afternoon, and remains relatively high until the late evening hours, after which it declines sharply. The black line in Figure A shows an example utility demand curve.

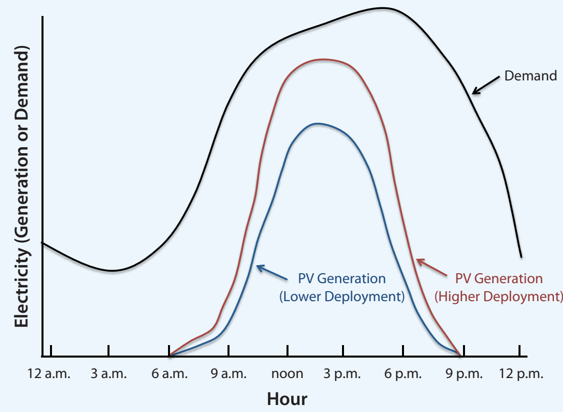


Figure A. Example Daily Electricity Load Curve and PV Generation Curves

The generation output from a solar system typically increases sharply as the sun rises in the morning and peaks around solar noon, before declining sharply as the sun sets. This pattern is represented by the blue line in the figure. As the number of PV systems connected to the grid increases, the peak of the aggregated PV generation curve grows, as represented by the red line in the figure. Note that as more PV systems come on-line, the difference between the electricity demand and the PV generation becomes significantly smaller during the peak hours of PV generation, but the difference stays about the same during other hours of the day.

The electricity demand curve minus the PV generation curve gives the net demand curve (also called the net load curve) for the utility. The net demand curve represents the amount of electricity demand that must be provided by the utility, taking into account the generation from distributed PV systems. As more distributed solar capacity comes on-line, the net demand curve changes shape. The depiction of this phenomenon for California's electricity system has come to be known as the 'duck curve' because of its duck-like shape (see Figure B, below). As the amount of PV generation increases, the belly of the duck grows larger since solar generation occurs primarily during the mid-day hours. As the amount of solar generation grows, there is an increasing need to ramp conventional generating resources down at sunrise and to ramp them back up quickly at sunset.

Advanced inverter functions and communication capabilities could provide at least a partial solution to the duck curve dilemma. If reductions in PV output can be anticipated, systems may be ramped down more smoothly, facilitating the transition to other generation sources. Other strategies include time-of-use (TOU) rates and demand response programs, which would help shift the time of demand on the system and further smooth the net demand curve.

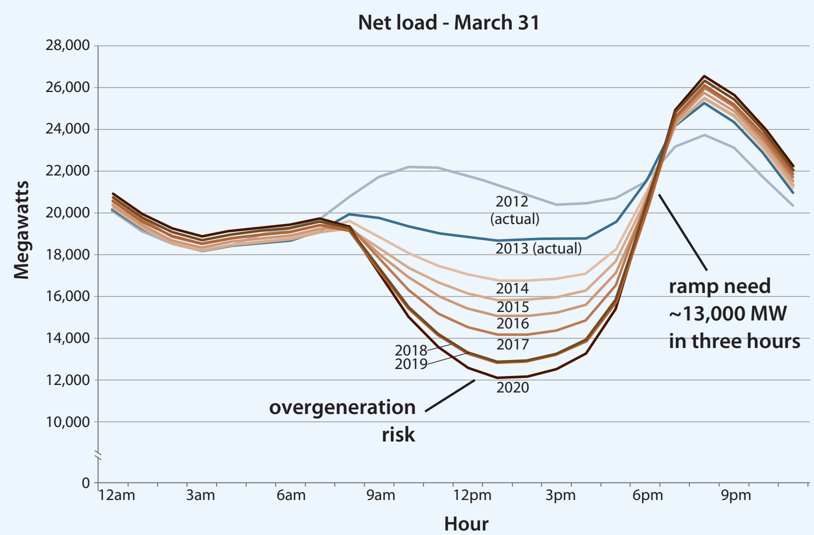


Figure B. An Illustration of California's Current and Estimated Net Load Curve - often referred to as the 'duck curve' (Source: CAISO 2013)

## Requirements and Payments for Grid Stability Services

As discussed in Text Box 1, there are several ways advanced inverter functions can provide reactive power compensation. Whether or not it is an economically viable alternative to traditional, centralized reactive power compensation depends on location-specific variables such as system operation costs, solar resource quality, and the degree to which generators are paid for the grid services they provide.

Regulatory considerations include whether distributed PV generators are required to contribute to voltage control on the distribution circuit through the provision of reactive power, how much of the time owners would be required to make these grid services available, and whether they are paid for this service to the grid. Compensation for voltage control services may include payment for the reactive power generated, for the income lost through solar curtailment, and for other grid services.

There is precedent for paying for reactive power services (FERC Staff 2014), although compensation to owners of PV systems connected at the electricity distribution level is very rare. One example is that of Georgia Power, which adopted an interconnection agreement that requires even small solar generators to provide reactive power using advanced inverter functions, and specifies that generators be paid for this service (Georgia Power 2013).

Regulations pertaining specifically to the curtailment of solar generation are most common in jurisdictions where the aggregate solar PV capacity can have an impact on system stability, and these regulations can be a stipulation of interconnection. In Germany, new and existing solar PV plants must be equipped with curtailment capability (De Silva 2013). Owners of small systems have the choice of either installing a remote management system, capable of curtailing system output to overcome grid congestion, or limiting the power fed into the grid to 70% of nominal capacity. Owners of PV systems are entitled to receive compensation for lost revenues ("Inverters and Grid Integration" 2013; Lang 2014).

## Updating Standards to Allow for Advanced Inverter Functionality

As discussed above, current U.S. standards require inverters to disconnect distributed solar systems from the grid when grid frequency or voltage is outside of a certain range. In some cases, the simultaneous disconnection of many systems puts grid stability at further risk. Although IEEE Standard 1547 has allowed for time-phased flexibility in disconnecting and reconnecting PV systems since 2003, jurisdictions and other implementers have not mandated the use of that flexibility to reduce that risk.

In May 2014, IEEE published an amendment (IEEE Standard 1547a) to its standard for distributed resources interconnection to the utility grid, allowing advanced capabilities for voltage regulation support and voltage and frequency ride-through. IEEE began working to address numerous recommendations for new or revised interconnection requirements to establish a more robust standard that will facilitate a higher penetration of distributed resources and the use of advanced inverter capabilities. Although IEEE has mandated that the process be completed by 2018, participants and stakeholders understand the pressing need to complete the process well before the deadline.

At the state level, a California Public Utilities Commission working group was recently tasked to make recommendations on policy changes to support the use of advanced inverter functions. These include defining new ranges that can be applied for under- and over-voltage and frequency ride-through, ramping and other functions to support grid stability under higher levels of distributed solar deployment (CPUC 2014). This work, which has been informed by experiences in Germany, may contribute insights regarding appropriate adjustments to operation standards in other regions of the United States (see Text Box 3).

## Considering Alterative Ownership Options

The owner of a distributed PV system typically also owns the associated inverter. However, other ownership structures could be considered, and may offer system benefits under higher levels of distributed generation. For instance, utility ownership of advanced inverters might provide opportunities for coordination and control that would further contribute to system stability, although the same benefits may also be achievable under customer ownership. Shifting the line where utility ownership ends and customer ownership begins could, however, address cost barriers for some customers wanting to participate in distributed generation. There are, of course, many regulatory changes that would need to occur to support the utility ownership model, including adjustments to regulations, interconnection standards, utility investment planning and PV system design and deployment (SEPA 2014). Ultimately, the costs and benefits of such an arrangement would need to be evaluated for each network or jurisdiction.

### Text Box 3: Deploying Advanced Inverters in Germany

By the end of 2010, Germany had about 14 gigawatts (GW) of distributed solar capacity connected to the grid. During the first six months of 2011, distributed PV provided 3.5% of the electricity generated in Germany. As higher levels of distributed solar are interconnected with the grid, there is increased risk that a rise in system frequency could trigger inverters to disconnect a large amount of PV capacity from the grid simultaneously. If frequency on the German system were to rise above the maximum level defined by existing PV interconnection standards (50.2 Hz), several gigawatts of solar capacity could potentially be disconnected at the same time. It was estimated that, in worst-case scenarios, 9 GW of solar capacity could potentially be disconnected at once, but the European grid was only designed to withstand the instantaneous loss of a maximum of 3 GW of capacity (Döring 2013). This problem came to be known as the "50.2 Hz problem."

In 2011 a multi-stakeholder working group set out to identify potential solutions to the "50.2 Hz problem" (VDE 2011). As a result of the group's recommendations, the German government passed the System Stability Ordinance (Systemstabilitätsverordnung) in 2012, requiring newly-installed distributed PV systems to reduce their output or shut down smoothly during high frequency events. Facilities of 10 MW or more commissioned before 2012 were required to be retrofitted by 2014 to comply with the new requirements. Older systems were allowed to retain instantaneous shut-off, but would have to be retrofitted to stagger their disconnections across a specified timeframe.

About 400,000 PV systems have been required to retrofit inverters to comply with the new standard. In the majority of cases, software updates or changes in the inverter operating parameters are sufficient for compliance. To limit the cost of mitigation, replacement of the inverter is discouraged. The total cost to retrofit existing systems was estimated to be between €65 million ($88 million) and €175 million ($238 million). Germany is working with other European countries to revise their over- and under-frequency protection standards for distributed generation (Bömer et al. 2011). As levels of distributed PV continue to increase in the United States, some lessons may be taken from the German experience. California's smart inverter working group is looking at adjustments to inverter operating standards for distributed systems (CPUC 2014).

The deployment of advanced inverters cannot be relied upon as the only strategy to integrate distributed variable sources of power into the grid. Other mechanisms to support increasing levels of distributed generation, such as grid upgrades and the adoption of energy storage, will have to be considered as well. Nevertheless, advanced inverters represent an option that is available, operational, and potentially cost-effective in the near term.

## ACKNOWLEDGMENTS

This paper was funded through the Department of Energy's SunShot initiative. Special thanks go to the many colleagues who provided useful feedback during its development, and in particular the efforts of Warren Leon (Clean Energy States Alliance), Barry Mather, Thomas Basso, Francisco Flores, Paul Schwabe, and Lori Bird (NREL).

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NREL/BR-6A20-62612 • November 2014

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