INVERTER TECHNICAL STANDARDS PROPOSAL

August 7, 2013

SUMMARY

Distributed generating systems, especially solar photovoltaic (PV) systems, are proliferating as prices have lowered and business models have become more sophisticated. These PV generation systems inject power at various points along electric lines, increasing the voltage of the electric lines at the point of interconnection. The power output from PV systems is also intermittent. Their output can change significantly over short periods of time due to environmental conditions like cloud movement and fog burn off. As the PV systems' output fluctuates, it causes voltage swings on electric distribution lines. Traditionally, to control the changes in voltage, utilities use specific equipment like load tap changers in the substation, line regulators and capacitors. However, the magnitude and frequency of the voltage swings is becoming difficult to manage using legacy electromechanical equipment as the aggregate number and size of PV and other distributed generating systems continue to increase. The voltage swings also cause the legacy equipment to operate excessively, requiring additional maintenance and operational costs, and early replacement.

One way to mitigate the voltage swings caused by PV systems and manage the voltage within the allowed operating range is to use inverters similar to those deployed in Europe with enhanced functionality like dynamic reactive power control. Early generation inverters and many simple inverters still manufactured in the US today can produce only real power (watts). They cannot produce reactive power (volt-amperes reactive, i.e. VArs). Most inverters produced for the US market today have the physical components required to provide enhanced functionality, but they lack the firmware, although increasingly the firmware is provided but not enabled. With only modest increases in manufacturing costs, firmware could be added during the manufacturing process to produce smart inverters with enhanced functionality that would generate or consume reactive power and mitigate voltage swings associated with PV systems.

Enhanced inverter functionality is also desired to achieve fault ride-through capability, so that PV and distributed renewable generators could contribute to grid stability during system disturbances where the grid voltage or frequency may go outside the normal operating ranges. Existing voltage trip settings prescribed in IEEE 1547 are conservative, forcing generators to trip off line quickly to avoid islanding. Conversely Germany has developed standards that require inverters to provide fault ride-through capability and dynamic reactive support. In fact, Germany has determined that it is necessary to retrofit 315,000 existing inverters to achieve enhanced inverter functions including low voltage ride-through (LVRT) capability in order to provide grid support during faults and voltage recovery during post-fault conditions to avoid a system blackout. The cost of the retrofit is approximately $300,000,000.

A standard requirement for communication capability would also enhance inverters' ability to support increasing penetration of PV systems by allowing remote function enablement or change of operating setpoint. Various communication protocols exist, however, a single protocol has not been identified as

a standard for use in inverters. Whatever protocols are adopted and implemented into inverter capabilities must be able to support security requirements required by electric utilities.

Given these considerations it is recommended to develop and implement technical standards that require new inverters to have the following functions:

- Communications capabilities
- Real and reactive power support
- Dynamic VAR injection
- Expanded frequency trip point
- Low voltage ride through
- Randomization of timing for trip and reconnection

VOLTAGE REGULATION

Historically electric utilities generated power in a central generating station and transmitted the power over high voltage lines to substations. The power was distributed radially outward in one direction over the distribution lines from the substations toward customers. As power flowed from the substations along the distribution lines out to transformers located near customers, the voltage in the distribution lines would be reduced.

Distributed generation sources, like customer owned photovoltaic (PV) systems, provide power generation sources at multiple points along electric distribution lines, frequently causing the power to flow back from the customer toward the utility. As power flows from distributed generation sources toward the electric utility, it offsets the power supplied from the substation and causes an increase in the electric distribution line voltage. If the distributed generator is large enough, it can raise the line voltage above the upper operating limit. Electric utilities are required to provide voltage to customers within a specific voltage range. The technical standard that prescribes the allowable voltage range with upper and lower operating limits is American National Standards Institute (ANSI) C84.1. The voltage limits prescribed by ANSI C84.1 are +5%/-5% for normal conditions, and +5.83%/-8.33% for short durations or abnormal conditions. To maintain the voltage on electric distribution lines within ANSI limits, utilities install equipment to adjust the voltage, like load tap changers in the substation and line regulators and line capacitors. Line regulators would adjust the voltage by transforming the voltage up or down. Line capacitors would inject reactive power onto the distribution lines, raising the voltage. In the past when power flowed in one direction, from substations out toward customers, line regulators and line capacitors were adequate to control the voltage and comply with ANSI voltage requirements. However, with the proliferation of distributed generation systems, it is becoming difficult and impractical to control dynamic voltage changes using traditional voltage management tools like line regulators and capacitors.

Conservation Voltage Reduction (CVR) programs have been implemented by utility regulators in various states in order to reduce operating voltages resulting in energy conservation.[1] Just as distributed

[1] In California this results in an allowable voltage range of +0%/-5%.

generation systems make it difficult to maintain voltages within ANSI operating ranges, they make it even more difficult to comply with the voltage reductions imposed by CVR programs. Roughly 70% of SDG&E's electric distribution system currently complies with CVR limits. Maintaining this level of compliance within CVR limits will be more difficult as PV penetration rates increase.

INVERTER TECHNOLOGY

Inverters used by PV generators convert DC power into AC power so it can be used by customers and interconnect with the electric grid. Early generations of inverters produced only real power, so the generated current was completely in phase with the voltage. This maximized the amount of watts generated, however it did not provide any reactive power which is needed to support real power flow.

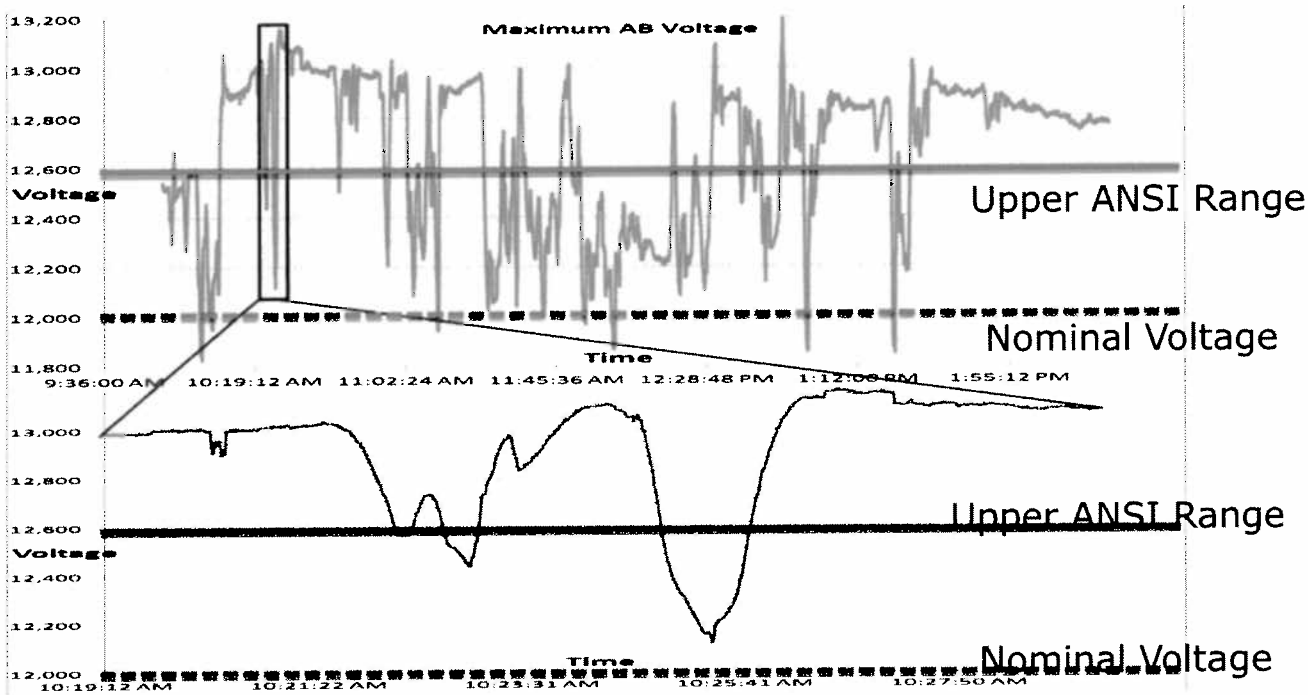
Later generation inverters with enhanced functionality can adjust the power factor to produce or consume reactive power. Adding reactive power, VArs, onto the distribution line will increase the voltage, while consuming VArs will decrease the voltage. This functionality will allow the smart inverter to reduce or mitigate voltage swings due to intermittent renewable energy sources.

Adding energy storage such as a battery to an inverter provides maximum operational flexibility by allowing four quadrant control, which means real power (watts) can be produced and consumed, and reactive power (VArs) can be produced and consumed. Energy storage connected to the grid through smart inverters is a very effective way to manage line voltage. Incorporating enhanced inverter functionality into inverters will facilitate the integration of energy storage systems in the future and increase the resultant benefits.

PV INTERMITTENCY ISSUES

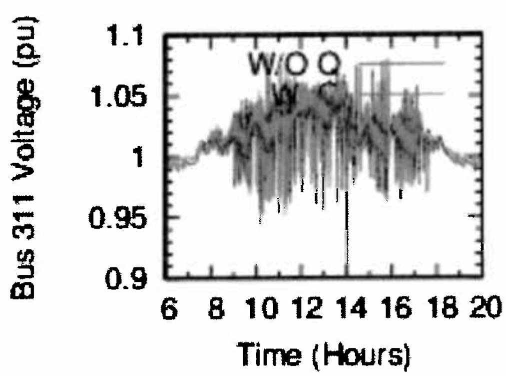
Electric distribution lines located in rural areas are typically comprised of long circuits using small wires. Small wires are adequate in rural areas because the electric loads are typically small and widely dispersed. Small wires have higher electrical impedance and subsequently see greater voltage swings than larger conductors used in urban areas. Large renewable energy systems are commonly located in low population rural areas where land prices are low and zoning laws will allow the installation of generators. Consequently it is not uncommon for multi-MW size PV generators to be located or to be proposed in rural areas, interconnecting to long distribution circuits with small conductor size. Locating even a moderate size generation source at the end of a long circuit with small conductor can produce significant voltage swings that are difficult to maintain within the upper and lower voltage limits prescribed by ANSI standards.

SDG&E has observed wide voltage swings on a particular rural distribution circuit with a 1 MW_{ac} PV system. These voltage swings are illustrated in the charts below. The upper set of curves illustrates the voltage swings over the morning and early afternoon of a single day during low circuit loading. The lower set of curves is an expanded view of a 10 minute period. The curves indicate voltage swings in excess of 10% and upper voltages well in excess of ANSI limits and CVR limits.

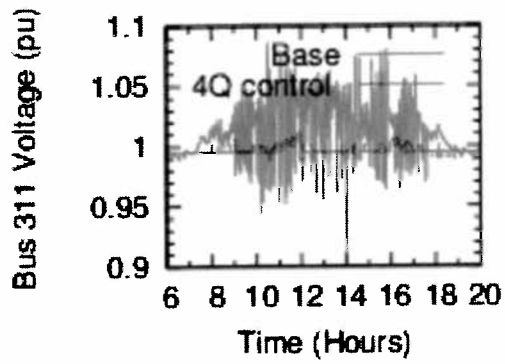


PV INTERMITTENCY MITIGATION USING SMART INVERTERS

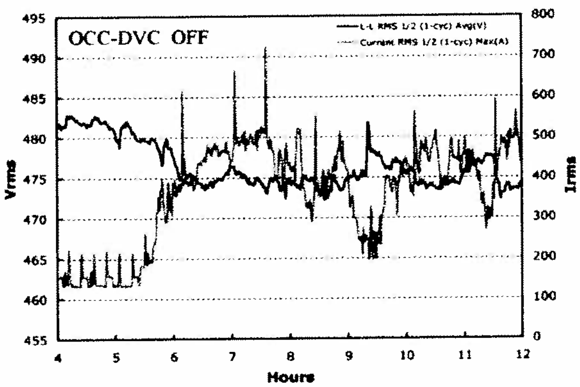
Modeled results: SDG&E performed modeling to determine the effectiveness of using inverter based equipment to mitigate the voltage swings associated with a large PV system located on a rural distribution circuit. The modeling study assessed the effectiveness of using inverter based equipment to mitigate voltage swings of a 2 MW PV generator at the end of a rural distribution circuit. The results shown in the chart immediately below indicate that using inverter based technology is an effective mitigation technique for voltage swings associated with a PV generator.



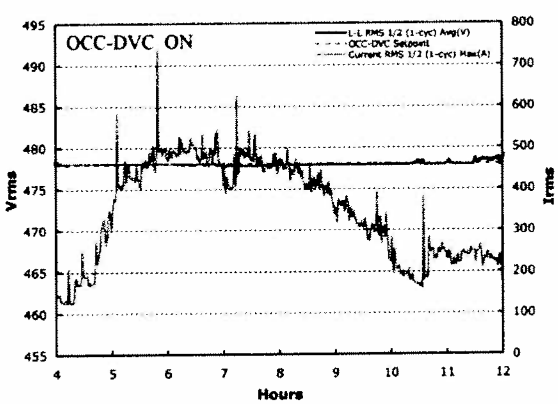
SDG&E also modeled the effectiveness of using inverter based technology plus energy storage. The results shown below indicate that using inverter based technology plus energy storage is even more effective at mitigating voltage swings than just using inverter based technology alone.



Measured results: SDG&E also has operating results from an inverter-based compensation device to provide dynamic reactive power control at a location in north San Diego County where a 384 kVA PV system has been installed. The first graph below shows the secondary voltage on a 1000 kVA 12kV/480V transformer serving an industrial customer before the installation of the inverter-based device. The 384 kVA PV is connected to the 480V secondary of the transformer.



The graph below shows the transformer secondary voltage after a 240kVA inverter based device with reactive power control was installed and operated. Clearly the inverter based device significantly improves the line voltage.



EXPANDED FREQUENCY TRIP POINT

As prescribed in IEEE 1547, inverters smaller than 30 kVA will disconnect at a grid frequency below 59.3 Hz, and inverters 30 kVA and larger have set points that are field adjustable. To ensure that PV systems and other distributed renewable energy sources provide grid support during system frequency events it would be desirable that inverters not disconnect too soon and that they disconnect in a random manner. During system under-frequency conditions it would be desirable that inverters do not disconnect until the system frequency drops to 57 Hz or below. During an over-frequency event it may be desirable to implement a ramp down in generator output as the frequency reaches a set point above 60 Hz, rather than a complete disconnection of the generator at a specific frequency.

LOW VOLTAGE RIDE THROUGH

Current technical standards require generators to trip off line at the following voltage levels:

- If line voltage at point of interconnection (POI) is less than 50% of nominal voltage, generator trips within 10 cycles
- If line voltage at POI is greater than 50% but less than 88% of nominal voltage, generator trips within 120 cycles
- If line voltage is greater than 110% but less than 120% of nominal voltage, generator trips within 60 cycles
- If line voltage is greater than 120% of nominal voltage, generator trips within 10 cycles

These trip settings were developed to isolate the generator quickly, reducing the exposure of the electric grid to unintended islanded operation. However, these limits may prevent a generator from staying on line during a temporary system disturbance, effectively worsening the impact of the disturbance. If generators could stay on line longer, they could provide a stabilizing effect on the system, possibly avoiding or reducing the need to drop load. Therefore it is desirable that broader limits be developed for inverters to facilitate low voltage ride through capability of renewable energy generators. It would also be desirable to have a feature that would allow slight variations in the time when inverters disconnect from or reconnect to the grid. This is desired in order to reduce the impact of large aggregate amounts of PV generators simultaneously disconnecting from or reconnecting to the grid. Enhanced inverter functions can support this through randomization of timing once the control decision/signal has been issued to trip or reconnect the PV system to the grid.

COMMUNICATIONS

It is important for inverters to have communications capability to allow utility operators to receive information from the field, issue control signals, and to override or change programmed settings. This capability to communicate is essential to supporting increased penetration of PV systems. While different communication protocols currently exist or are under development, no single protocol has been identified as a standard that all inverters should comply with. However, whatever protocols are adopted and implemented into inverter capabilities must be able to support the security requirements of SDG&E and other electric utilities.

COST FOR ADDED INVERTER FUNCTIONALITY

The additional manufacturing cost to install firmware upgrades on inverters to enable them to provide dynamic voltage control plus other enhanced inverter functions is estimated to be about 10% during initial implementation of the new functions during manufacturing process.[2] Current retail costs for inverters typically range between $.50 and $1.00 per watt, so the expected increase in cost is expected to be less than $.10 per watt. It is anticipated that over time the additional firmware installed to facilitate the enhanced inverter functions will be integrated into the normal manufacturing process, and therefore the incremental cost to make inverters with enhanced functions will decrease.

INVERTER STANDARDS IN GERMANY

Germany has experienced tremendous growth in renewable energy generating sources like PV and wind systems. To better manage the operations of the electric system as PV and wind generators increased their penetration, BDEW, the industry association of grid operators and electric utilities in Germany, created guidelines for inverter capabilities. While these guidelines are not required by law, electric utilities require interconnecting generators to comply with the BDEW guidelines, in effect turning the guidelines into standards requirements.

The BDEW guidelines provide specifications for generator control and communications, frequency control, dynamic reactive support, dynamic grid support including low voltage ride-through, and certification as described below.

- Generator control and communications: Generators larger than 100 kVA must provide on-site or remote control of generator output, and they must provide a communications platform to the electric utility. Generators smaller than 100 kVA must also comply with this requirement unless they limit their maximum output.
- Frequency control: Inverters are required to provide over frequency control, where generator output is gradually reduced above frequency set points.
- Dynamic reactive support: Inverters are required to provide variable power factor to control voltage rise.
- Dynamic grid support: Inverters are required to provide reactive current during voltage dips, and also provide low voltage ride-through to prevent early disconnection during system disturbances.
- Certification: Inverters must undergo defined certification process that includes separate evaluation steps for accreditation and modeling.

REGULATORY ACTIVITIES

The California Public Utilities Commission has issued an Order Instituting Rulemaking (OIR) R.11-09-011, which covers distribution level interconnection rules for electric generators and storage. Phase I of this

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[2] This estimate of the incremental cost to provide inverters with enhanced functions has been verified in discussions with inverter manufacturers.

OIR pertaining to the Rule 21 Settlement for SDG&E was finalized in 2012. In some sections of the Rule 21 Settlement IEEE 1547 language has been adopted directly, and in other places IEEE 1547 requirements were paraphrased. Phase II, which includes technical operating standards for smart inverter functionality and generator output, is proceeding through scheduled workshops with a goal to adopt the "smart" inverter functionality described within this paper.

FERC issued a Notice of Proposed Rulemaking (NOPR) RM 13-2-000 to revise the pro forma Small Generator Interconnection Procedures and Small Generator Interconnection Agreements, which establish the terms and conditions under which utilities must provide interconnection service to generators 20 MW or smaller. This NOPR also discusses grid frequency issues that can be addressed by smart inverters. Therefore, it represents an opportunity to achieve broad based support under FERC to develop technical standards for enhanced inverter functions.

RECOMMENDATIONS

SDG&E recommends the development and implementation of inverter technical standards for the following functions:

- Communications capabilities
- Real and reactive power support
- Dynamic VAR injection
- Expanded frequency trip point
- Low voltage ride through
- Randomization of timing for trip and reconnection

SDG&E proposes application of standards requiring the implementation of these functions on all new inverters.

It would be desirable for all inverters to have these enhanced functions. However, retrofitting inverters in existing generation systems would be much more expensive than implementing the enhanced functions on new inverters. In the future it may be appropriate to consider replacement of existing inverters with enhanced inverters, especially in locations where the benefit realization is significant and justified.