ADVANCED INVERTERS FOR DISTRIBUTED PV:

Latent Opportunities for Localized Reactive Power Compensation

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Executive Summary

Reactive power is a ubiquitous, critical, and complex feature of the modern electrical network. Careful, localized management of reactive power is key to a smoothly-operating grid; mismanagement of it can lead to catastrophic blackouts, as was the case in New York in 2003. One opportunity for localized management is the use of advanced inverters coupled with distributed PV systems to provide reactive power adjacent to the point of use. Advanced inverters allow system operators to control the output characteristics of PV-generated power, allowing provision or withholding of reactive power as appropriate.

Germany is one of the world leaders in installed PV capacity and as of 2012 has been using advanced inverters to manage local voltage via reactive power. In particular, Germany passed new grid codes that require PV systems to be capable of frequency dependent active power manipulation during abnormal grid conditions as well as reactive power provision during normal gird operations. The provision of reactive power may involve a tradeoff with active power supply depending on system design and thus these new grid codes have implications for the economic efficiency of PV systems. The reactive power control literature has generally shown that fixed reactive power control is the most costly form of reactive power regulation when compared with variable reactive power control that fluctuates with either active power output or local voltage.

To evaluate the feasibility of a Germany-like system in the US, we studied the provision cost to both consumer and utility to identify a status quo 'value' for reactive power. Our analysis indicates that distributed PV-generated reactive power is uncompetitive with conventional utility-provisioned reactive power. Critically, however, our analysis does not account for costs associated with transmission of reactive power, which contribute strongly to overall costs.

We identified several drivers of advanced inverter reactive power adoption and studied their interdependencies. While inverter capital cost is shown to be improving at rates too slow to be impactful, we believe there is great latent opportunity in highly location-specific reactive power provision. Particularly, in regions where electricity is expensive (and thus, presumably, so is conventional reactive provision) and inverter capacity factor is at 90% or lower (either due to inverter oversizing or non-ideal sun

conditions), reactive power can be generated at minimal cost to the system operator. Understanding the subtleties of this argument will be the focus of our future work.

Overview: Goals and Objectives

In discussions with the Clean Coalition, we identified three key knowledge areas to explore:

1) Reactive power for a general audience (Section I)
2) Germany's management of distributed PV systems and advanced inverter-produced reactive power (Section II)
3) Sensitivities of potential reactive power valuation models (Sections III & IV)

Section I: Reactive Power and the Advanced Inverter Opportunity

Reactive power is the AC-component of power at any instant in a circuit (Diagram A), and results from the present of capacitive or inductive loads in a circuit or system. Reactive power can be thought of as power that oscillates between the load and the source, as opposed to real power, which is the power that is delivered to the load; in a simplified explanation, real power is the power available to 'do real work.' Because significant inductive and capacitive loads are found in numerous electronic devices (e.g. arc welders, consumer electronics, CFL bulbs), reactive power is a necessary fixture of modern society.

However, reactive power's critical ubiquity brings ubiquitous critical challenges to the electrical grid. Widespread literature exists on the subject (Miller, 1982), but the most urgent challenges presented by reactive power are overloading of transmission lines and management of voltage fluctuations. Overloading of transmission lines is significant: if a large component of apparent power stems from reactive loads, the transmission line still experiences the apparent power – even though only a fraction of that power is usable as real power. Thus, if lines transmit poor-quality power to intensive real loads, there is a serious danger of overloading the capacity of that line. Voltage fluctuations due to excessive reactive power in the system can lead to collapse of an entire electrical grid; voltage fluctuations due to insufficient reactive power management is cited as a key reason of the 2003 New York-Toronto blackout (FERC Staff Report, 2005; Grudinin & Roytelman, 1997).

To avoid the above dangers, reactive power's presence must be 'compensated' in an electrical grid. That is, reactive power must be deliberately produced locally, adjacent to the inductive or capacitive load, such that the reactive power is balanced. Load compensation serves to increase power quality – measured by power factor (Diagram A) – by directly balancing reactive power. Voltage regulation seeks to provide reactive power at levels that manage temporal over- and under-voltages to avoid blackouts.

State-of-the-art compensation strategies involve placing static (motionless) or dynamic (moving) compensators in shunt or series configuration with the source of reactive power (Dixon *et al* 2005). Traditionally, compensators were mechanically switched capacitor or inductor banks that shift current in the appropriate (leading or lagging) direction, or adjustable speed motors that could alter their spin speed and direction to provide appropriate alternating current. In recent decades, integrated thyristor-switched capacitors and capacitors, functioning together as a Flexible AC Transmission System (FACTS), and later solid-state- and power electronics-based compensators, allow increasingly rapid and exact provision of reactive power. Globally, static reactive power production is estimated to be greater than 100 GVAr (Tyll and Schettler, 2009), representing nearly 1% of the estimated 15.8 TW average power production globally (Energy Information Administration, 2008).

Reactive power provision is complex because of the difficult of transmitting it over long distances (Tufon *et al*. 2009), demanding localized production adjacent to the source of reactive power. The wide deployment of distributed generation systems, such as residential photovoltaic systems, further exacerbates this challenge – increasingly distributed voltage fluctuations will result from power generation at multiple interconnects, requiring greater, careful reactive power provision (Turitsyn K *et al*. 2011).

Distributed generation does not only bode negatively for reactive power provision, however. There is significant potential to turn the requirement of increasingly localized reactive power provision into an opportunity for a new market for reactive power generation based on key components of residential photovoltaic systems.

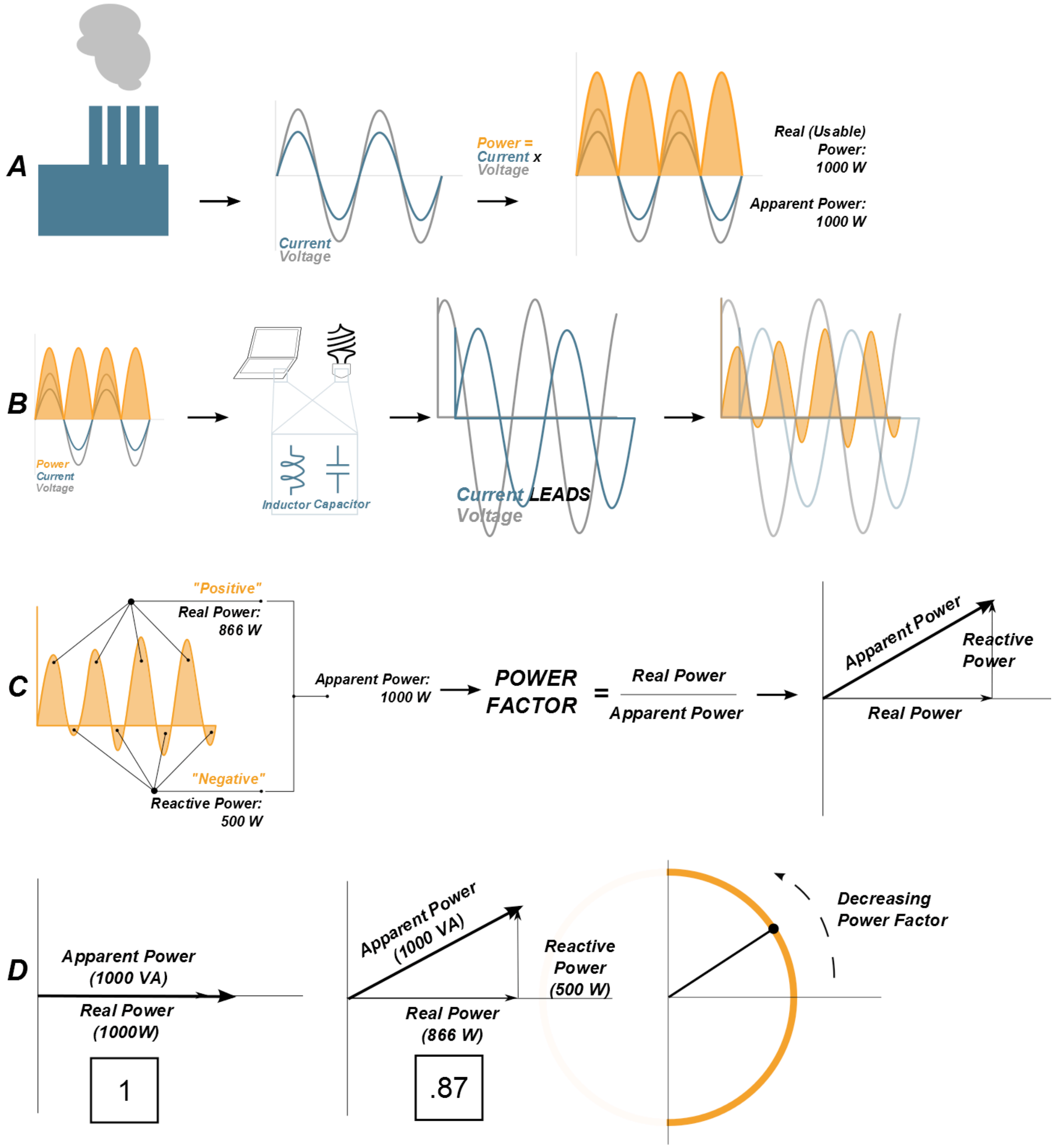

Diagram A. Reactive Power: an Introduction. Conventional power is produced from a turbine in a plant, produced current and voltage that are perfectly in phase (a), creating a power waveform that is positive, even when current and voltage are negative. When such a power waveform traverses the grid, it inevitably encounters reactors (inductors or capacitors), fundamental circuit elements found in everything from transformers to computers to CFL bulbs (b). These elements shift the current out of phase from the voltage (capacitors cause the current to ‘lead’ the voltage, as shown, while inductors cause the current to ‘lag’ the voltage). This changes the power waveform to be ‘negative’ at certain times in the cycle. Positive peaks are described to be real power that is usable to do real work, while the negative peaks represent reactive power, power that flows back towards the source from the reactor (C). This reactive power is unusable but takes up transmission bandwidth. Power engineers use power factor, a ratio of real, usable power, to the apparent, overall power, to describe the power components in the system. Power with low power factor contain significant amounts of reactive power and less real power (D), and can be visualized by plotting real power versus reactive power on a coordinate axis. Power engineers represent power factor graphically using a unit circle, where the radius represents the constant

Distributed photovoltaic generation systems consist, at a basic level, of a solar panel, an inverter, and a grid interconnect. Upcoming PV systems will have the opportunity to use advanced inverters, which provide interesting opportunities related to reactive power production (Fig. 1). Advanced inverters, combined with existing FACTS infrastructure and control systems, could offer hyper-localized management of reactive power – for example, in response to localized voltage fluctuations, all PV systems in a certain area of the distribution grid could modulate their AC output power factors to respond appropriately to grid fluctuations.

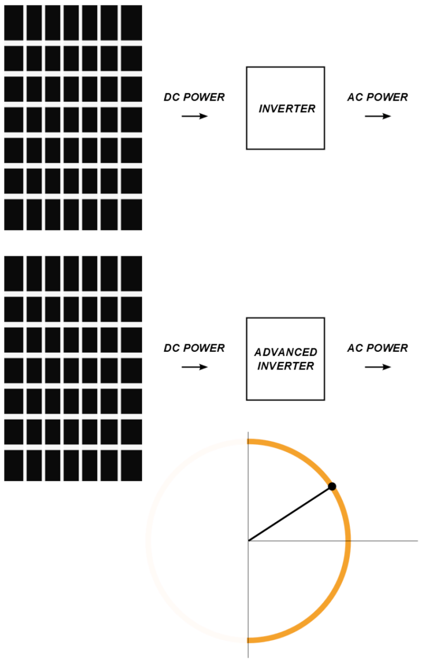

Figure 1. Advanced Inverters in PV Systems. Conventional PV systems follow the schematic at top, in which an inverter converts DC power from a solar panel to AC power at a fixed power factor. In the case below, an advanced inverter allows precise determination of the power factor of the AC power supplied to the grid, allowing dynamic response to operator control.

Modulation of power factor comes at a price, however – by operating at a lower power factor, system operators forgo real power that they otherwise might have produced (Fig. 2). Thus, provision of reactive power from distributed PV systems demands that utilities or grid operators provide system operators with some incentive for production of reactive AC loads. The nature of this incentive – whether it's a state law or financial compensation – will be explored in the rest of this report.

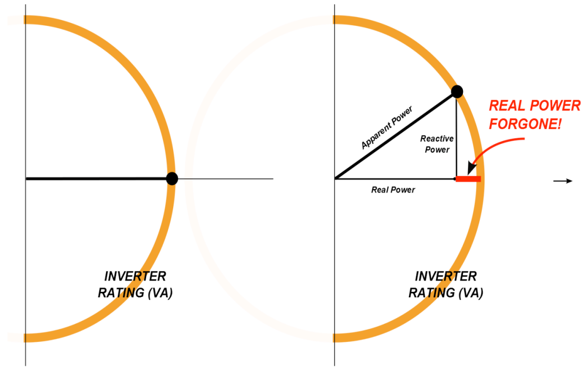

Figure 2. Real Power Loss from Non-Unity Power Factor. If system operators run their system at unity power factor (left), they output real power as specified by the inverter rating. However, if the operator runs the system at a power factor below unity, the operator forgoes a certain quantity of real power to generate reactive power (right).

Section II. Photovoltaics and Reactive Power Control in Germany

Methods

Our analysis of Germany’s state of the art in regulating reactive power via advanced inverters coupled to distributed photovoltaic (PV) systems involved a comprehensive examination of the scientific, regulatory, and technical literature related to Germany’s experience and actions associated with such reactive power control.

Distributed Solar Energy Generation in Germany

Germany is currently the world leader in installed solar PV energy capacity and much of this capacity is installed as distributed, small-scale systems. As of January 2013, more than 32 gigawatts (GW) of PV capacity were connected to the German grid (Marten, 2013) and supplied 3 -10% of the country’s electricity (Plumer, 2013). Of this total installed capacity, approximately 8.8 GW are produced by small-scale PV plants with individual capacities of less than 30 kilowatts (kW) each (Stetz et al., 2013). Moreover, 70% of the country’s PV capacity is connected to what is considered the low voltage grid (Marten, 2013; see Figure 3) which operates at voltages up to 1 kilovolt (kV) while primarily serving private households, small businesses and the agricultural sector.

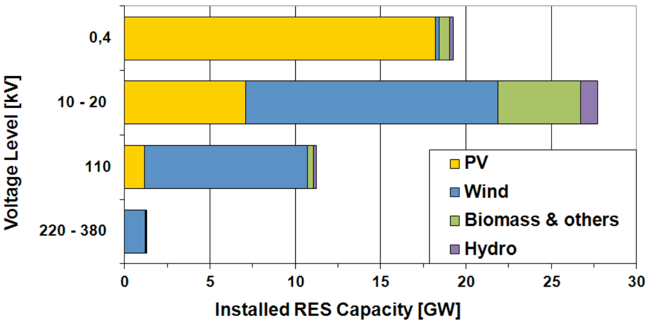

Figure 1 Figure 3. Installed renewable capacity at different grid levels in Germany (Marten, 2013)

Grid Stability Challenges

While Germany has installed large amounts of solar PV, this PV capacity is not uniformly distributed throughout the region and high PV penetration in localized areas has lead to system stability and power quality concerns. The average nationwide

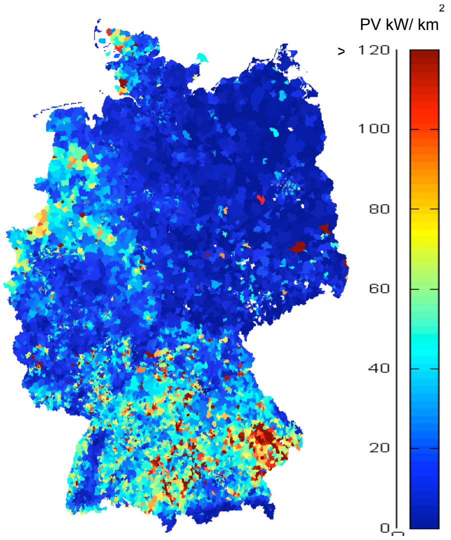

Figure 4. Average concentration of installed PV capacity (kW/km^2) by zip code in Germany (Stetz et al., 2013)

concentration of installed PV per unit land area in Germany is approximately 39 kW/km^2, however some regions are experiencing extremely high local levels of PV penetration that exceed 200 kW/km^2 (Stetz et al., 2013; see figure 4). The integration of such high concentrations of PV generation onto the grid can lead to system stability and power quality problems. Two particular problems that have been of primary focus in Germany are issues with frequency regulation and voltage rise. These issues have sparked concerns about the potential need for cost-intensive grid reinforcement as more PV capacity continues to be connected to the grid (Man, 2012; Stetz et al., 2013)

Frequency regulation

To ensure grid reliability, system operators in Europe must maintain the electrical frequency on the grid within a tight range around 50 cycles per second (hertz (Hz)). Prior to 2011, German grid codes related to frequency regulation required PV system inverters connected to the low voltage grid to automatically shutoff (disconnect) active power output within 200 milliseconds (ms) when network frequency fell outside the normal operational range of 47.5 – 50.2 Hz (Man, 2012). However, if such a shutdown were to occur during high power infeed from numerous distributed PV systems, it could result in sudden, extreme power variation that would inhibit frequency stabilization (VDE, 2012). Moreover, simultaneous re-connection of the decentralized generators in the course of a frequency recovery could elevate network frequency above 50.2 Hz, thus causing the generators to shut down again, a problem referred to as the "yo-yo effect" or the “50.2Hz problem” (VDE, 2012).

Voltage rise

Electrical devices need power of an appropriate quality to operate correctly when plugged into the network. In large part, this requires that electricity be supplied at a voltage that is within a specified range of the nominal or operational voltage for which the system is designed or at which the system is regulated (e.g. 230V in Germany) (Markiewicz and Klajn, 2004). The permissible supply voltage[1] range for medium- and low-voltage grids in Germany is defined by the standard DIN 50160, "Voltage Characteristics of Electricity Supplied by Public Distribution Networks," which limits the supply voltage variation at a generator's connection point (CP) on the grid to a maximum of 3% of nominal voltage (Man, 2012, KEMA 2011). Due to Ohlmic resistance along transmission and distribution lines, active power feed-in from numerous distributed PV systems can lead to local supply voltage magnitudes outside the acceptable range, necessitating additional network voltage regulation by the distribution system operator (DSO) to preserve power quality.

Germany's New Grid Codes

Given the existing and expected future increases in renewable generation capacity (primarily distributed PV systems) installed on the low-voltage grid as well as concerns about the impacts of this penetration on grid stability and power quality, the German Association for Electrical, Electronic & Information Technologies (VDE) adopted new grid codes in 2011 under the directive VDE-AR-N 4105 [2] (Engel, 2011; Man, 2012). The new directive took effect on August 1, 2011 with a transitional period through January 1, 2012, and among its specific requirements are mandates that generators connected to the low-voltage grid provide grid voltage support via reactive power control during normal operations and contribute to frequency regulation via active power manipulation under abnormal grid conditions (Engel, 2011). Meeting these new grid codes is largely expected to be facilitated by advanced inverter functionality that allows distributed PV systems to be more flexible in providing services that promote grid stability and power quality (Man, 2012).

Frequency regulation

In order to avoid grid destabilization due to immediate disconnection of large generation capacities when the network frequency ($f_{network}$) is outside the normal range of 47.5 – 50.2 Hz the new grid code requires

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[1] Utilities define two primary network voltage levels: supply voltage which is the voltage at a generators point of connection to the grid, and utility voltage which is the voltage level an electrical device experiences when plugged into an outlet on the network.

[2] Prior to 2011, interconnection to the low voltage grid was regulated under Grid Code Directive VDE-0126-1-1. This directive had no requirement for distributed generators to contribute to voltage regulation and in terms of frequency regulation, specified inverters needed to immediately disconnect if network frequency fell outside of normal range.

frequency-dependent active power reduction by generators instead of automatic shutoff. The directive states that in the case of over frequency (when 50.2 Hz < $f_{network}$ < 51.5 Hz) generators must decrease or increase instantaneous power output (P_M) at a rate of 40 % of P_M per hertz such that $\Delta P = 20 (P_M) [(50.2Hz - f_{network})/50.2 Hz]$, where P_M is frozen at the point in time the network frequency of 50.2 Hz is exceeded (Geibel et al., 2011; VDE, 2012). However, this new directive still requires generators to disconnect from the grid (within 100 ms) in cases of extreme over- or under-frequency $f_{network} \leq 47.5$ or $f_{network} \geq 51.5$ (Geibel et al., 2011).

Grid voltage support

To aid in the regulation of grid voltage and maintain network power quality, the new German grid code requires generators connected to the low-voltage grid to be capable of supplying reactive power (Q) to the network during normal operation. The reactive power control requirements specified in the new grid codes depend on the installed system size and whether that system has a remote connection to the distribution network operator so it can receive reactive power control signals (Stetz et al., 2013; Stetz, 2011). Any renewable energy system with an installed capacity of less than 30 kW that doesn't have a remote connection to the network operator must limit active power infeed to 70% of the maximum apparent system power (S_{max}) regardless of the current state of the grid (Man, 2012). If the system is remotely connected to the network operator, it must be capable of providing reactive power by operating across a range of power factors[3] (Man, 2012). The specified range depends on the S_{max} of the system as follows:

- S_{max} < 3.68 kilovolt-Amps (kVA) - the generator is considered a micro-generator and should operate with a power factor range of ±0.95 in accordance with German grid codes for the connection of micro- generators in parallel with public low-voltage distribution networks;
- 3.68 kVA $\leq S_{max} \geq$ 13.8 kVA - the generator shall accept any set point from the network operator within a power factor range of ±0.95.
- Smax > 13.8 kVA - the generator shall accept any set point from the network operator within a power factor range of ±0.90.

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[3] As previously explained in this document, power factor is the ratio of real to apparent power and is equal to cos φ (where φ is the phase angle between the current and voltage).

While the new low voltage grid codes specify the operational power factor ranges for reactive power control, the distribution network operator determines the reactive power control method. There are three primary control methods proposed by the new low-voltage grid codes: fixed power factor, power factor characteristic, and reactive power/voltage characteristic.

Under the fixed power factor (cos φ) method, a PV systems inverter will operate at a static power factor supplied by the network operator (see Figure 5). This method is primarily suitable for systems where the active output generation is constant. Given the intermittent nature of output generation from distributed PV systems, the grid codes recommend using either the power factor characteristic or reactive power/voltage characteristic methods if possible (Man, 2012).

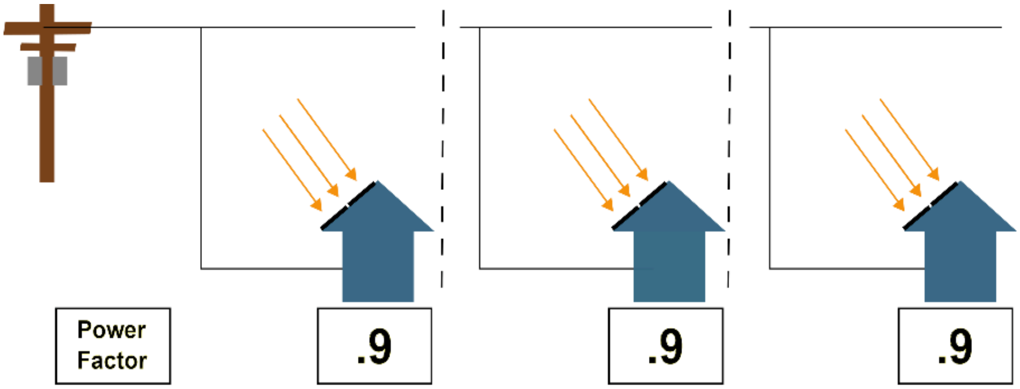

Figure 5. Illustration of the fixed power factor method; Each system operates at the same set power factor.

With the power factor characteristic (cos φ (P)) method, the reactive power provided depends on the active power fed in by the generator at its point of connection to the grid (CP). For example, in Figure 6, each system is experiencing a different level of insolation and presumably outputting a different amount of active power, thus each system operates at a different power factor. Under this method, reactive power output is automatically regulated by the system's inverter based on a droop characteristic curve supplied by the network operator. According to the droop curve specified by the low-voltage grid code, when the system's instantaneous active power output reaches half of the rated active power of the inverter (P_n), the power factor decreases towards 0.9 (Man, 2012). The reactive power supplied can be expressed as $Q = \tan(\operatorname{acos} \varphi)P_n$ (Man, 2012).

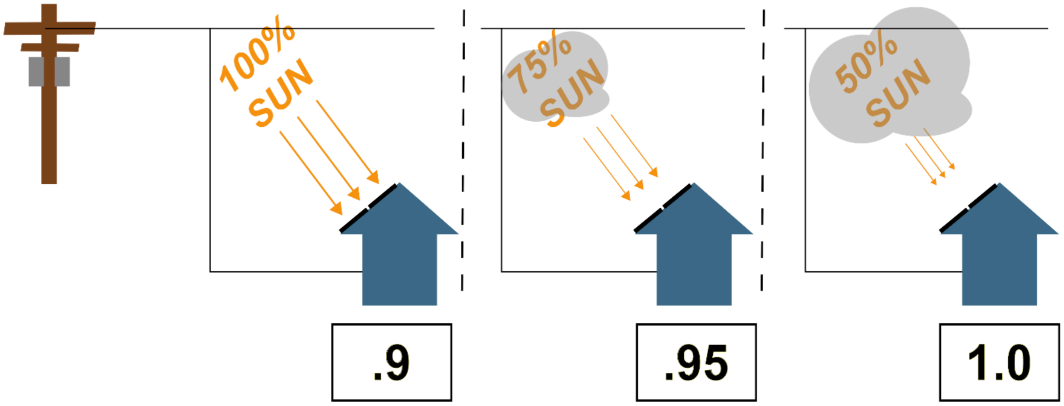

Figure 6. Illustration of the power factor characteristic method; systems operate at different power factors due to different active power output.

Unlike the previous two methods, the reactive power/voltage characteristic or Q(U) method relies on local voltage information in the reactive power control process. Under this method, the reactive power output by a generator's inverter is proportional to the voltage level at the generator's CP to the grid (Man, 2012). This is illustrated by Figure 7, where each system is experiencing a different local voltage level and is thus each is operating at a different power factor. In this case the droop curve must be provided by the DSO based on the load flow characteristics of the specific network and the reactive power output is calculated as $Q = \varsigma\, Q_{max}$, where ς is the value of the voltage variation (Man, 2012).

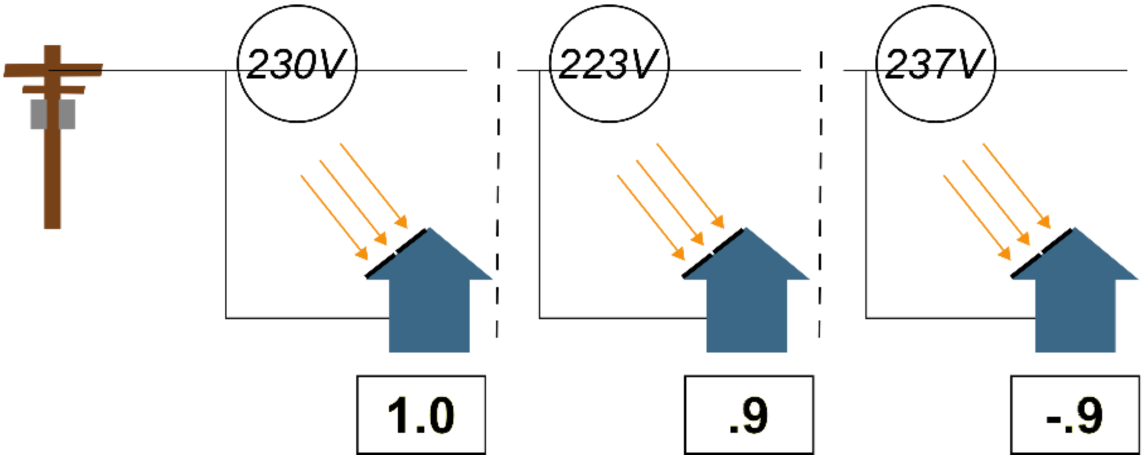

Figure 7. Illustration of the reactive power/voltage characteristic method; systems operate at different power factors due to different local voltage.

Reactive Power Compensation and Efficiency of Reactive Power Control Methods

The grid voltage support required by Germany's new low-voltage grid codes may involve trade-offs between active and reactive power production in a PV system if Sqrt $[P(t)^2 + Q(t)^2] > S_{max}$ (where P(t)=active power output at time t, Q(t)= reactive power output at time t, and S_{max} is the maximum apparent power) (Stetz et al., 2013). Stetz et al. (2013) conduct an economic analysis of different reactive power control methods and use a reactive power compensation value of 0.0087 Euro (€)/ kVArh (citing this as the rate paid by German energy company E.ON) as compared to an active power compensation value of 0.28 €/ kWh. Thus, as illustrated in Figure 8, because the provision of reactive power can lead to a reduction of active power feed-in, it can negatively affect the profitability of a PV generator (Stetz et al., 2013). According to Stez et al. (2013), the owner of a PV generator must bear the costs for reduced active power feed in, however, EEG (2012) requires that DSOs compensate generators for the reactive power they supply.

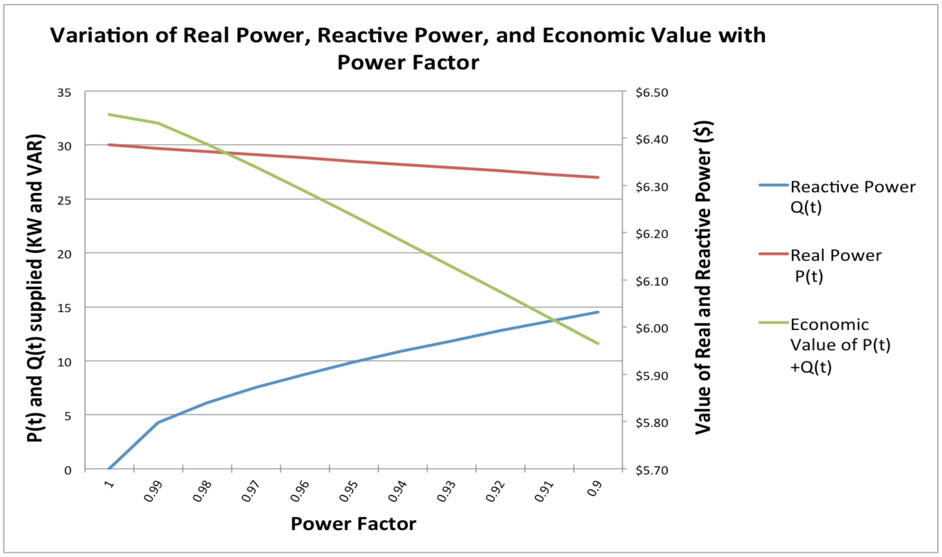

Figure 8. Variation of real power, reactive power, and value of real plus reactive power with power factor. Assumes a 30 kW PV system with 30 kVA inverter and values of $.215 and $.011 for real and reactive power respectively.

In terms of economic efficiency, it is therefore desirable to minimize reactive power provision in order to maximize active power supply from each generator. Given this, a constant power factor is not the optimal reactive power control strategy for intermittent DG (Esslinger & Witzmann, 2012). Stetz et al. (2013) find the fixed power factor method led to the highest annual total cost for reactive power control in a hypothetical low voltage grid. In contrast, they found considerable economic savings potential from the application of variable reactive power provision (Stetz et al., 2013). Esslinger and Witzman (2012) note that the power factor characteristic control method reduces active power losses compared to a constant power factor. However, this control strategy does not completely minimize the additional reactive power that is provided by inverters and still results in some unnecessary active power losses (Esslinger & Witzman, 2012). This occurs because the method does not use any grid voltage information and thus reactive power may be consumed by an inverter even though the voltage at the generator's point of connection is in an admissible range (Man, 2012). Moreover, this method can also result in a situation where below the same transformer on a feeder, every generator with the same active power generation (P) will absorb the same amount of reactive power regardless of their distance from the transformer even though generators at the end of the feeder experience greater impedance along the distribution lines and greater voltage variation, as shown in figure 9 (from Man, 2012).

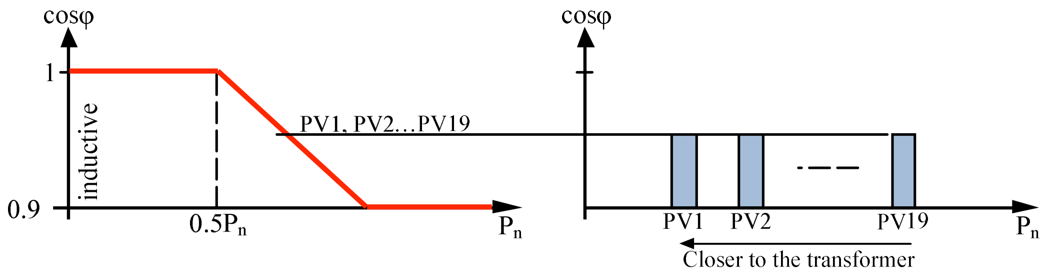

Figure 9. The power factor characteristic droop curve is shown on the right and the graph on the left shows that this method can result in inefficiency due to PV systems operating at the same power factor despite higher voltage variation as distance from the transformer increases (Man, 2012).

Esslinger and Witzman (2012) conclude that the reactive power/voltage characteristic method is even more efficient than the power factor characteristic method as it limits the additional reactive power flow and active power losses on the network. However, because the voltage magnitude at network connection points closer to a transformer will likely to be within the regulated limits the majority of the time (Figure 9), increased burden falls on the inverters of generators further from the from the transformer and can shorten their lifetimes and place increased costs on the oweners of these systems (Man 2012). Despite this, Man (2012) concludes that because of the higher levels of reactive power consumed by all inverters with the power factor characteristic method when compared to the reactive power/voltage characteristic method, more inverters experience shorter lifetimes with the power factor characteristic method, costing more overall.

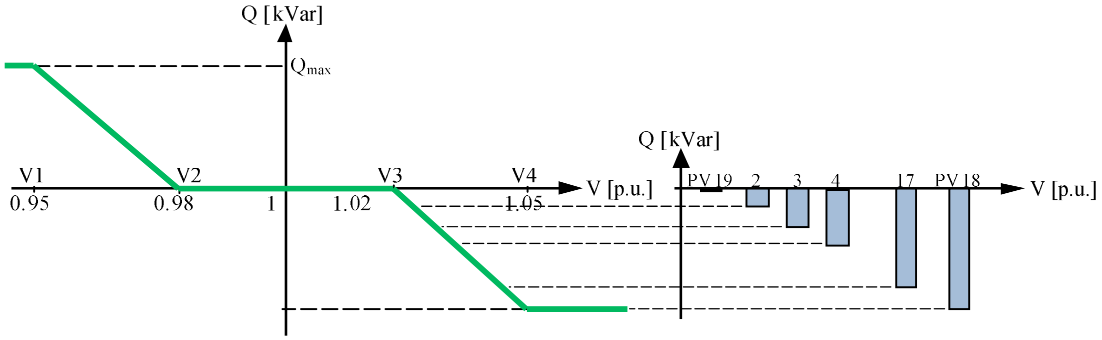

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Figure 10. The reactive power/voltage characteristic droop curve is shown on the right and the graph on the left shows this method results in PV systems further from the transformer efficiently supplying more reactive power (Man, 2012)

New Grid Code Implementation

Implementation of the frequency regulation and reactive power control requirements mandated by the new German grid codes requires advanced inverters capable of frequency dependent active power reduction and reactive power provision. This has necessitated changes in how new inverters are manufactured and, in certain cases, retrofitting or replacement of existing inverters to incorporate these new functionalities.

Frequency regulation

Prior to April 2011, solar inverters designed for deployment in Germany were preset by manufacturers to disconnect from the grid at a frequency of 50.2 Hz but in accordance with the new grid codes, inverters must now be preset for frequency dependent active power reduction. In July 2012, the German Federal Council passed the *Ordinance on Grid System Stability – SysStabV* requiring retrofitting of certain existing PV system inverters to comply with the new frequency control measures established under the new low voltage grid codes (BSW Solar, 2012). The ordinance mandates retrofitting of PV systems connected to the low-voltage network that were commissioned before January 1, 2012 with an installed capacity greater than

10 kW and that don't already comply with the frequency control regulations in the new German grid codes (BSW Solar, 2012). However, pursuant to Section 4 of the ordinance, distribution network operators, not PV system owners, are responsible for ensuring that the inverters of solar power plants connected to their grids comply. The VDE estimates that around 9 GW of PV capacity consisting of approximately 315,000 PV systems will require retrofitting (BSW solar 2012). The estimated costs of this retrofit, EUR 170 million for retrofitting and EUR 20 million for administration, will be borne by the electricity consumers, with 50% charged in grid fees and 50% as part of the EEG surcharge (Lang, 2012b). This retrofitting has to be completed within a period of three years following a system size- staggered timetable that ends December 31, 2014 (Lang, 2012a and 2012b).

Grid voltage support

In terms of reactive power control, the German Parliament adopted an amendment to the Renewable Energy Act in July 2011 imposing new requirements that inverters on distributed generators be capable of receiving remote communication from network operators to allow power factor signals or droop characteristics to be transmitted by the network operator to inverters (Corfee et al., 2011). The requirements apply to new PV installations and existing installations above 30 kW installed before 2012 (Corfee et al., 2011). Specific time limits within which existing installations must comply were set based on system capacity (Corfee et al., 2011). Existing systems above 100kW were ordered to comply within 6 months of the law going into effect (or by July 2012) and those between 31-100 kW that were installed in 2009 or later are mandated to comply by 2014. As previously mentioned, generators below 30 kW must either have a remote communication capability or permanently limit their active power injected into the network to 70% of their total installed capacity (Corfee et al., 2011).

It appears to vary by manufacturer as to whether retrofitting of existing inverters or inverter replacement is required. Inverter manufacturer SMA, states "it is not possible to upgrade an inverter without reactive power capability into an inverter with reactive power capability" (SMA, 2010), while another manufacturer, SolarEdge, claims their inverters can be upgraded using configuration steps and labeling to indicate the inverter is now LVGC (low voltage grid code)-compliant (SolarEdge, 2011).

III. Cost Models for Reactive Power

Methodology

We have taken a look at the current state of the art in reactive power generation and distribution in Germany, and will apply that knowledge to discover a range of reactive power solutions for the US. There are a multitude of options that can be weighed and compared, however, for the sake of brevity, this analysis is going to consider two main solutions: 1) utilities can produce their own reactive power or, 2) customers can produce reactive power and feed it back into the grid for a fee. It is expected that it will prove most cost effective for utilities to compensate customers to provide reactive power. This should favor both utilities and customers, in that utilities will save in ensuring there is proper voltage control, while customers will be able to amortize the cost of their PV systems with the compensation paid to them for producing the reactive power.

Cost to Customer to Produce Reactive Power

As Germany has shown, end-users of electricity who have, or will, install photovoltaic systems on their property can be a great resource for locally-distributed reactive power. Through their inverters, these customers can locally inject the amount of reactive power that is needed in their local grid, saving utilities some of their need to build large reactive power generation stations. The analysis focuses on two methods which customers can use to generate reactive power: by 1) downgrading their power factor (which may cause them to lose peak real power), and 2) oversizing their inverter.

Customer Downgrades Power Factor

In the first method, customer A would own an inverter that is sized to their photovoltaic system. For instance, if the PV system produces a 10 kW output, then the inverter would be sized to convert 10 kW of DC to AC power. The only way for customer A to produce reactive power is to run their system at a power factor less than 1. This will not impact customer A financially during the majority of the day (when the sun is low on the horizon, or it is cloudy), but it may impact him during peak solar insolation, when the sun is high in the sky, and there is no shading. At this time, customer A would be producing the maximum amount of energy from his

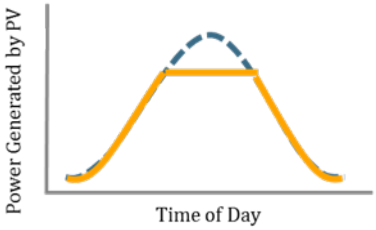

Figure 11: Customer A loses peak real power when: Insolation is at maximum AND customer A must run at a power factor < 1.

PV system, and may be running at a power factor of 1. However, if regulations state that he must always run at a power factor of 0.9, for example, he will be losing some of the peak real power, as shown in Figure 11. Thusly, customer A will lose energy, and hence money, due to regulation. In this case he should be compensated for that loss. The value of that compensation is what needs to be found.

To look at an example, consider a system (and inverter) size of 10 kW located in San Francisco. Assuming a daily peak that lasts an average of 2 hours, and that the customer must run at a power factor of *PF* = 0.9, he will lose (*Peak Insolation/day)(365 Days/yr)($0.149/kWhr)(PV System)(1-PF)* = $109/kVAR-yr in peak real power. This value uses an electricity cost of $0.149/kW-hr, and an inverter life of 10 years. However, the compensation will vary regionally, as insolation and cost of electricity varies widely throughout the US.

Customer Oversizes Inverter

It is possible for the customer to produce reactive power while not losing any peak real power, however. For this, the customer will oversize his inverter. In this case, customer B will own an inverter that is larger than is necessary for his PV system, which will guarantee that he runs at a power factor less than unity. The loss for customer B in this case would be the extra cost of the larger-than-necessary inverter. Customer B would be compensated for this extra cost.

Take for example, the instance where customer B has a 10 kW output PV system, and a 12 kW inverter. The extra cost compared to a 10 kW inverter would be $113.5/kW (according to the current cost of SMA inverters). If customer B were also required to run at a power factor equal to 0.9, he will produce 1.2 kVAR. Based on the difference in inverter costs, customer B will lose (*Cost Difference of Inverters) / [(Inverter Life)(PV Size)(PF)]* = $2.4/kVAR-yr. Note that this value also uses an inverter life of 10 years.

It is readily apparent that customer B is spending the least for reactive power. For the customer, it seems that oversizing the PV inverter is the best of the two reactive power production options, at only $2.4/kVAR-yr. However, it is important to note that this is a very brief analysis which looks at two very specific cases. This conclusion may not hold true across every region of the US, as electricity costs and insolation, as well as reactive power needs vary widely. Furthermore, inverters vary in cost, and oversizing tends to become more cost effective as size increases, as seen in Figure 12 below. Oversizing from an inverter size of 8 kW to 9 kW will cost only $0.35/kVAR-yr, which is an intriguingly small cost.

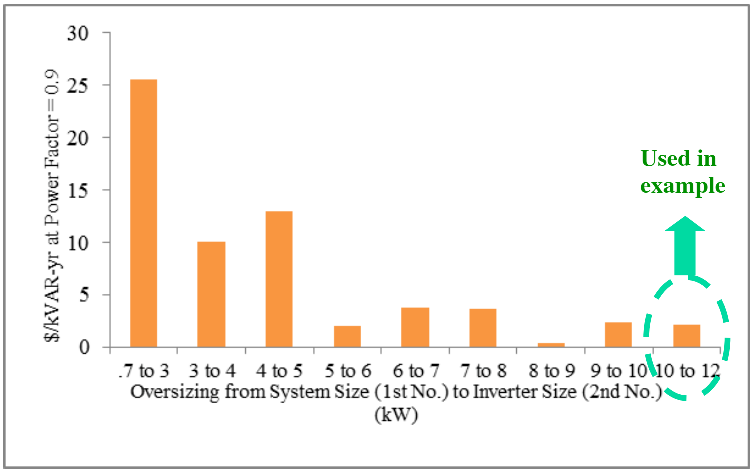

Figure 12: Cost of inverter oversizing per kVAR-yr at a constant power factor of 0.9. Each bar represents cost of oversizing from system size (1st number on horizontal axis) to inverter size (2nd number).

Cost to Utility to Produce Reactive Power

Utilities use a number of methods to produce reactive power at a large scale. At a number of locations on the grid, these technologies compensate for voltage by delivering reactive power when needed. The most common of the technologies used are capacitor banks and synchronous generators.

When connected to the system, large shunt capacitors cause current to lead voltage. This compensates for the load, which causes current to lag. Capacitor banks are made up of large capacitors that can be hooked up to or disconnected from the system by switches [Turitsyn 2011]. As reactive power needs rise, more capacitors are switched on. However, reactive power cannot travel far. Instead, it decays rather quickly with distance over power lines. Thus, utilities must determine the optimal location for the capacitor banks as well as the optimal number of capacitors to continuously switch on or off. This becomes a large and challenging problem to solve, especially as more and more homes and PV systems come online.

For the purposes of this analysis, we will look at the costs associated with capacitor banks. Another option which could possibly be implemented is utility ownership of advanced inverters on end-user properties.

Utility Installs Capacitor Banks

Capacitor banks are commonly used by utilities to produce reactive power. Unfortunately, research turned up very few data points as to the cost of installing and running a capacitor bank. The Clean Coalition team was graciously able to provide one useful data point, however: a 1200 kVAR capacitor bank would cost $25,000 with a 15 year service life, amounting to a cost of $2.3/kVAR-yr for the utility.

Utility Owns Oversized Inverters on End-Users' PV Systems

Utilities may have another option available to them: to have ownership of end-users' inverters. In this case, the costs will be similar to those found in the customer ownership of oversized inverters – approximately $2.4/kVAR-yr. It may be more cost effective for the utility to own the oversized inverters, compared to customer, due to tax incentives given to the utilities for their equipment. However, this needs to be studied in more detail.

Cost Models: Conclusions

Overall, it seems that producing reactive power by oversizing PV inverters is the most cost effective option of the 4 considered. However, it is unclear whether the oversized inverters should be owned by the utility or by the end-users. Also, the 4 example cases that were studied are very specific, and do not take into account a number of variables, such as location, intermittency, transmission line upgrades, or distance from new capacitor banks to areas needing reactive power for voltage control. In addition, assumptions and simplifications were made in the cost models discussed, which may need to be revised in a more detailed follow-up study. On the other hand, traditional methods of reactive power generation such as capacitor banks have a number of drawbacks, from issues of equipment damage caused by transients when switching the capacitors on and off, to high-frequency harmonics that cancel the effectiveness of the generated reactive power [Turitsyn 2011].

Section IV. Inverter Deployment Sensitivities

Out of several possible drivers of widespread advanced inverter utilization for reactive power provision, our analysis indicated that four were most promising: inverter costs, local power costs, local insolation and solar capacity conditions, and operating power factor. We studied cost independently, and then considered local conditions and power factor as a system. We believe that these factors will be essential pieces of any valuation strategy of advanced inverter-produced reactive power.

Inverter Costs

Advanced Inverters represent a ‘moving target’ technology with rapid advancement and significant differentiation between subsequent products. As described previously, a key strategy for reactive power provision via advanced inverters is to ‘oversize’ the inverter. However, in many markets, inverter costs play an important role in governing the cost-effectiveness of oversizing, and indeed, the deployment of advanced inverters. Available data (Figure 13) indicates that cost reductions due to traditional learning curve models will be themselves insufficient to drive technology adoption.

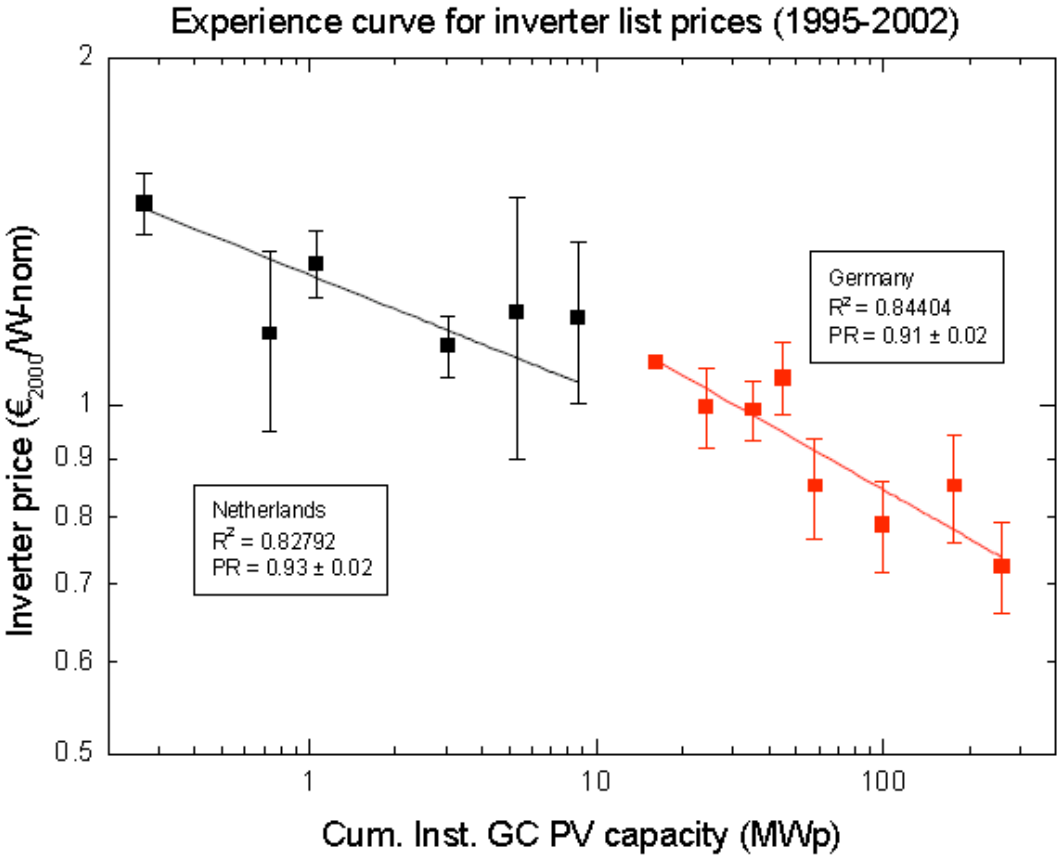

Figure 13. Inverter cost trends (Schaeffer *et al.* 2004). Historically in Europe, inverter prices have demonstrated extremely shallow learning curves – 7% in Holland, and less than 10% in Germany - relative to installed capacity. Because x-axis data on installed PV capacity is displayed in log scale, significant reduction in advanced inverter cost will not occur in the near future.

Local Insolation, Energy Pricing, and Operating Power Factor

As explained previously and further expounded in Diagram A, **power factor** describes the amount of reactive power relative to the real power in a given AC power waveform, and thus defines a given advanced inverter's reactive power production.

The economics of advanced inverter-driven of reactive power are highly sensitive to **local power costs** - operators 'give up' real power to produce reactive power, and thus lose more money in locations where power costs are high.

Finally, insolation, or capacity factor, plays a key role in reactive power production. Insolation and inverter oversizing both take advantage of capacity factor to deliver economical reactive power (Figure 14). Thus, in locations with insolation insufficient to run the inverter at full capacity, it costs the system operator nothing to run at a reduced power factor and produce reactive power.

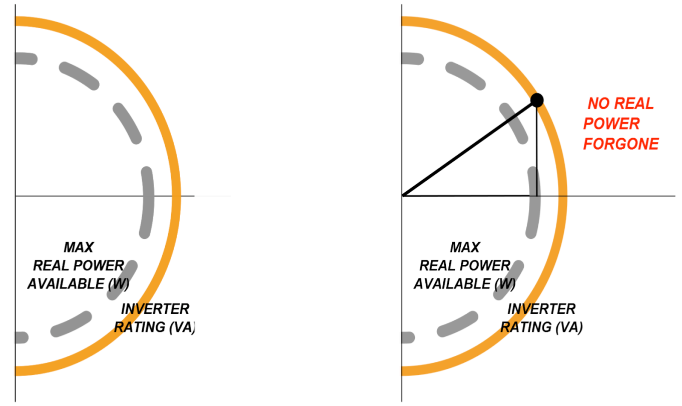

Figure 14. Capacity Dependence of Power Factor. As shown at left, an inverter is sized for a particular rating (orange line), but given solar conditions can deliver a maximum real power condition (grey dashed line). This discrepancy could be a result of either (a) non-optimal insolation conditions or (b) an intentionally oversized inverter. In the case at right, a power factor is chosen such that maximum real power is made available, yet reactive power is still produced.

For a given array size A, a power factor PF, and an insolation capacity IC, local cost of electricity K ($/kWh), time of one year (h), and interest return factor I (1%), we develop the following equations to describe the *minimum compensation value* for breakeven reactive power production, $Value_{compensation}$.

$$P_{PF,i} = A * PF;$$

$$S_{IC,i} = A * IC;$$

$$Value_{compensation} = (S_{PF,i} - P_{PF,i}) * K * Y * I$$

$$Value_{compensation} / kVAr = (Value_{compensation}) / (P_{PF,i} * \tan(a\cos(PF)))$$

Using these equations, and noting that for conditions where S = P, e.g. non-ideal insolation conditions at high power factor, $Value_{compensation}$ is zero, we develop Figure 15.

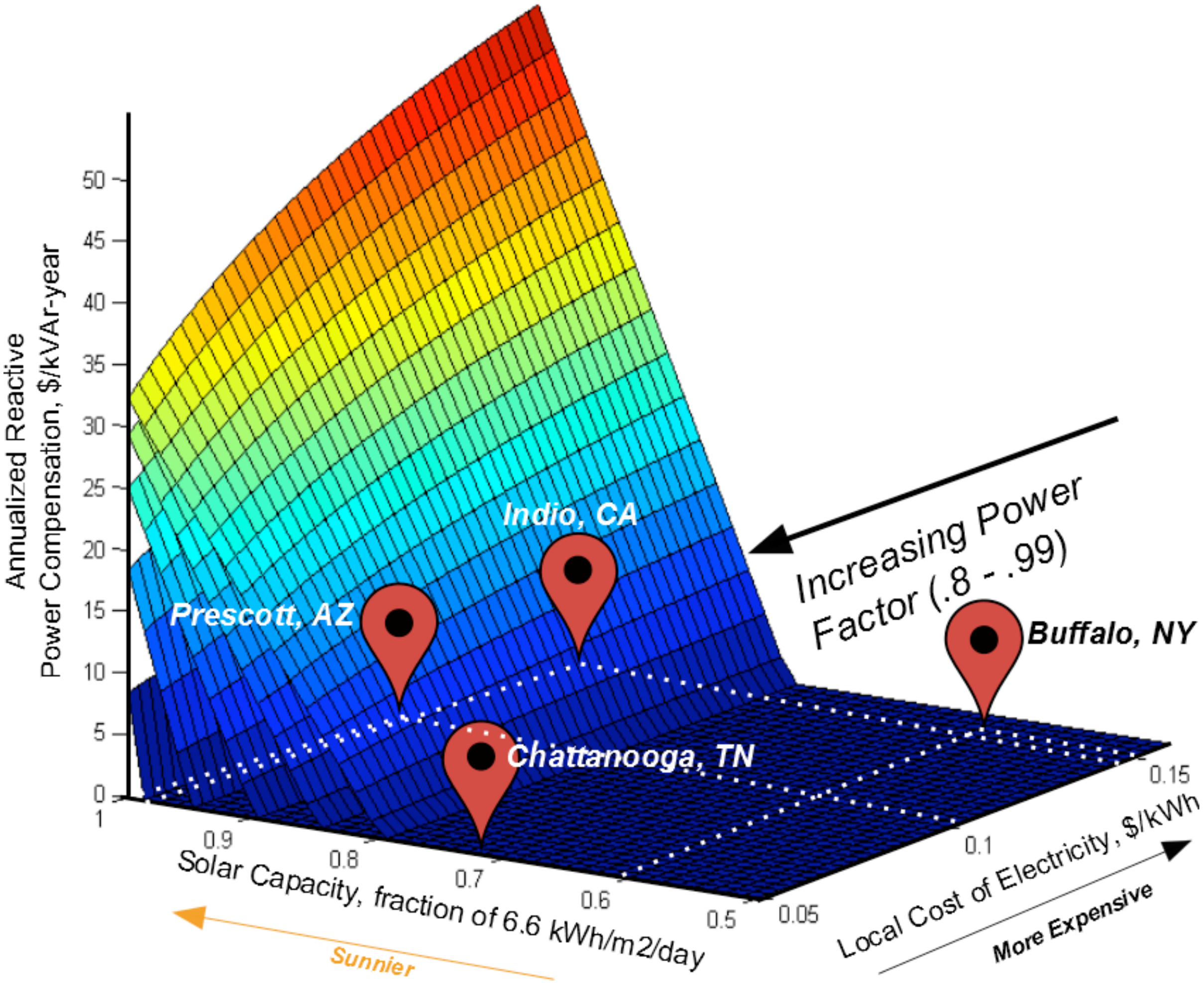

Figure 15. Location Sensitivity of Minimum Breakeven Value for Reactive Power Compensation. Surfaces left to right indicate decreasing power factor, from .99 at the bottom to .8 at the top. At high power factors, annualized compensation need only be minimal, while at lower power factors, e.g. .8, annualized compensation must be significant to offset the loss in production of real power. Location is critical in determining this, however. Location-specific data was collected from PVWATT, and suggest that places with intensive sun and high electricity costs (Indio, CA) are highly sensitive to power factor fluctuations, while even a 30% reduction in solar capacity (Chattanooga TN and Buffalo NY) opens up the possibility for minimal reactive power compensation, despite relatively high local power prices.

Based on this analysis, we conclude that system operators need to be highly aware of local conditions in considering an advanced inverter reactive power generation strategy. Counterintuitively, locations with lower solar capacity overall offer utmost flexibility and loss-independence in reactive power production; locations with high solar capacity must carefully consider potential losses associated with reactive power production and incentivize system operators accordingly.

Section V. Limitations and Conclusions

Limitations

1) Analysis of Germany: Key information in foreign language (German); policies are brand new (1-year old), meaning little analysis was available.
2) Price and Sensitivity Modeling: enormous number of variables to consider, and limited information on each. We chose highly specific cases to analyze, which themselves are sensitive to a large number of factors.
3) Unavailability of data: certain key information, such as transmission expenses of reactive power, specific prices of installed conventional kVAr generation systems, etc., were unavailable and prevented certain key analyses

Conclusions

1) Reactive power is a ubiquitous feature of the modern electrical grid that demands careful local compensation. One promising compensation strategy is the use of advanced inverters coupled to PV systems to for local reactive power management.
2) Germany is actively managing reactive power and frequency regulation via advanced inverters coupled to PV systems and their experience provides successful examples of legislation and implementation strategies while also demonstrating that there are differing economic efficiencies associated with various reactive power control strategies.
3) Current market conditions indicate that conventional reactive power supply systems are cost-favorable to advanced inverter generation of reactive power. Further analysis, accounting for the distance-based loss of reactive power, is needed to make a fair comparison.
4) Any valuation of reactive power requires careful consideration of local factors, critically, power and insolation.

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