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Smart Inverters and Their Role in the Modern Electric Grid

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SUMMARY

Distributed energy resources (DERs) are a solution for many challenges in the electric power grid. Primary drivers of their adoption include an aging infrastructure (requiring significant capital expenditure), capacity constraints where traditional utility upgrades may not be feasible or economical, and localized demands on utility distribution infrastructure (due to customer choice to add solar photovoltaic (PV), energy storage, or electric vehicles). The operational profile of these technologies, when observed as a collective group, are often characterized by random load/generation profiles which can create disturbances in supply voltage and power quality, ultimately impacting the safety and reliability of power delivery.

One of the prominent sources of renewable energy in widespread use is solar photovoltaic (PV) power generation. The high penetration of PV based DERs is threatening the reliability of power delivery due to intermittency (result of cloud coverage) and lack of temporal coincidence of maximum production with peak load. Energy storage is one way to address this problem.

PV and energy storage systems rely on inverters to deliver solar PV production, or energy from batteries, to connected loads. The inverter takes direct current and converts it to alternating current at a voltage and frequency that matches the grid. Battery energy storage systems incorporate a charger, allowing the energy from the grid, or co-located PV where available, to replenish the stored energy. Advanced types of these inverters, known as smart inverters, combine intelligence and communications with the traditional power conversion capabilities of a standard inverter, enabling a range of capabilities that can address many of the challenges of large-scale DER integration.

This paper focuses on the role of smart inverters, specifically in the context of distribution operations. The paper also identifies challenges and highlights questions and uncertainties that should be addressed in advance before any large-scale deployment of smart inverters is pursued.

KEYWORDS

Smart Inverter, Energy Storage, Volt-VAR, Volt-Watt.

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INTRODUCTION

Every distributed energy resource (DER) that connects to the electric grid uses an inverter to convert direct current (DC) into alternating current (AC). Historically, these devices lacked any form of advanced functionality. Their primary role was the conversion of some form of DC to AC, generally without regard to power factor, and for solar PV, at maximum output capacity, commensurate with input power (solar) and their individual conversion efficiencies. Aside from localized maintenance requirements or, perhaps, remote-connected maintenance and firmware updates, solar inverters were not designed to establish any form of real-time interaction with users. The traditional business case for solar PV was maximizing output at all times. There was no desire to curtail output, as this would change the economics and negatively influence total return.

Energy storage systems (ESS) modified this paradigm slightly. By allowing assets to charge or discharge as necessary to perform their desired role, the always-on/always maximum output of the PV inverter operation has changed. ESS need some form of communications capability to accomplish these on-demand features, which creates a quasi two-way interaction with the user.

Overshadowing all of these developments were the requirements established by standards. UL 1741, together with Supplement A (UL 1741 SA), govern the safety of DERs [3]. These UL standards establish the connect/disconnect criteria for DERs that are currently being interconnected to the power grid. IEEE standard 1547 [2], which will eventually replace UL 1741, expands upon UL 1741 by describing requirements surrounding stand-alone capabilities (so-called “Autonomous Functions”) as well as communications and interactive advanced capabilities (“Advanced Functions”). To comply with UL 1741 standards and the updated IEEE 1547-2018 standard, inverters have transitioned into interactive devices, which enable capabilities that provide potential benefits for distribution system operations. These interactive devices are “smart inverters” (SIs).

In order for a smart inverter to perform the autonomous and advanced functions, fundamental capabilities within the controls must exist. For example, PV and ESS inverters must have capabilities to adjust power factor (known as adjustment of P (real power) and Q (reactive power)), to adjust output power as a function of measured line voltage or frequency, and to set thresholds regarding maximum power that can be output (PV and ESS) or consumed to charge energy storage (ESS only). There are notable differences between solar PV inverters and storage inverters, and these differences can limit the intended use and the resulting business value of using inverters to address power distribution-related issues.

Inverters, depending on their design and application, can operate in one, two, or four power quadrants[1]. PV inverters are generally two-quadrant devices but single-quadrant units are still commercially available. ESS inverters are four-quadrant devices due to their charging/discharging capabilities.

Figure 1 illustrates four operating power quadrants. In Quadrants 1 and 4, the inverter generates real power with leading (absorbing VARs) or lagging power factor (injecting VARs). In Quadrants 2 and 3, the inverter absorbs real power with leading (absorbing VARs) or lagging power factor (injecting VARs).

[1] Inverters that do not control reactive power are not a subject of this article.

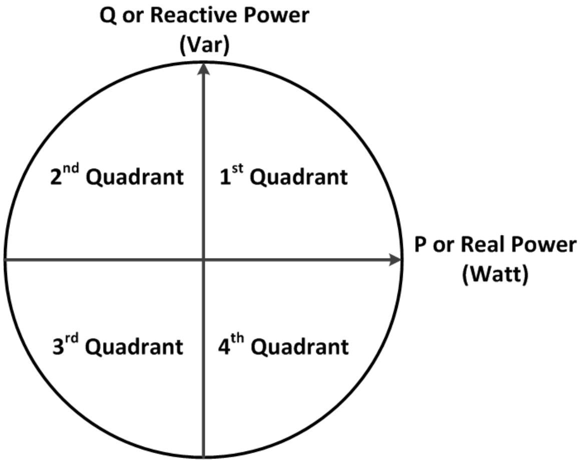

Figure 1. Four Power Quadrants

Operation of inverters in Quadrants 2 and 3 is only possible if the DC side of the inverter can absorb, dissipate, or store energy; therefore, inverters used in an ESS utilize the four power quadrants to perform intended functions.

Significant benefits can be gained with the four-quadrant system as compared to the two-quadrant system. With proper operational firmware in the inverter, the four-quadrant system can independently control real power P and reactive power Q, providing a wide range of functions including power factor correction, active filtering, and independent charging / discharging while adaptively adjusting reactive power to compensate for line voltage changes. Further, because of the DC-DC coupled nature of the PV and energy storage system, excess PV production can be absorbed directly and efficiently by the ESS. Each of these functions uses some combination of the four quadrants operation, resulting in significantly increased capabilities and enabling the asset to perform many functions that can be utilized to improve utility distribution operations, and potentially to offset expenses for customers.

Figure 2 (Left) shows representative schematic diagrams of a two quadrant inverter versus a four quadrant inverter. Note that in a two-quadrant inverter, the reactive power output (Q) cannot be adjusted independently from the active power output (P), which itself is a function of real-time PV output if connected to solar cells. As PV real power output (P) varies, the reactive power (Q) changes in proportion to P. This proportionality suggests that most PV inverters, which are generally two-quadrant machines, are limited in their functionalities, which subsequently limits their capabilities in addressing power distribution issues. Also shown on the right side in Figure 2, is an energy storage inverter co-located with a PV system. Independent of the presence of the PV, the battery energy storage provides additional functionalities including independent control of real power P, and reactive power Q. The resulting independence of the two power parameters expands the capabilities of the inverter to address a broader range of technical and business use cases. Subsequent sections describe a number of these use cases.

Co-locating the PV system and the ESS permits direct charging of the battery with PV output, thus improving overall efficiency of the system. The co-location of PV and energy storage is a trend that is becoming more prevalent in power distribution systems due to the increase in efficiency and improved economics.

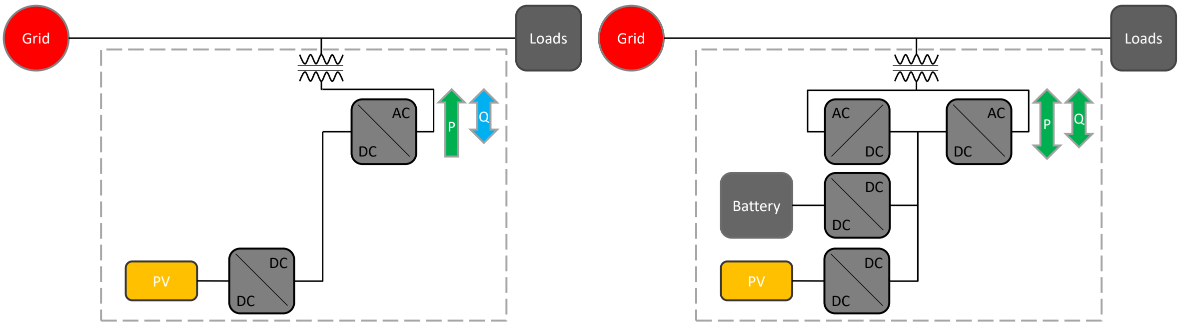

Figure 2. Schematic of a Two Quadrant Inverter (Left) versus a Four Quadrant Inverter (Right)

The capability of advanced inverters to communicate interactively with an external control entity is the fundamental requirement of being a "smart inverter". Real-time communication enables smart inverters to respond to power and control commands, which allows utilities to use them as a dispatchable asset for capacity or ancillary services. Utilities can address many of their existing challenges by the deployment of smart inverters with smart inverter-enabled services such as:

- Reliability / Resiliency
- Frequency Response (FR)
- Volt/VAR Operations (VVO)
- Power Factor Correction
- Peak Shaving
- Load/Generation Following

The following section discusses a system level problem that utilities with high penetration of PV in their network have been facing. A solution using smart inverters is also discussed. Figure 3 shows simple diagrams showing the interactive communication links between utility and DERs (DER is using smart inverters).

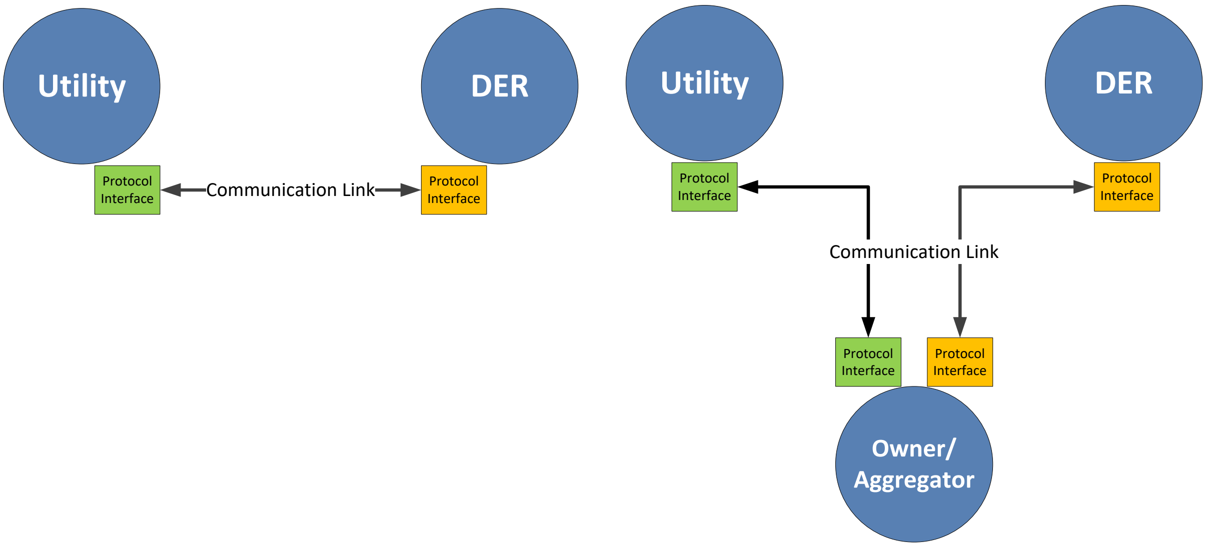

Figure 3. Simplified Topology for Communication between Utility and DERs using Smart Inverters

HISTORICAL PROBLEMS AND NEW SOLUTIONS

Non-Synchronized Generation versus Demand (Duck Curve)

Without availability of compensating energy storage, the daily generation profile of PV systems does not correlate well with the system load profile as their production peak times and ramping rates significantly differ. Peak PV generation, which is contemporaneous with the solar irradiance peak, occurs in the early afternoon. In contrast, peak consumption generally occurs in the morning when a majority of residential customers prepare to leave home as well as in the later afternoon and early evening as they return home. On a system-wide scale, PV production can be equivalent to mid-day load, causing a significant drop in total demand (called "masked load"). If PV production is too high, the excessive generation can even cause subcircuits to experience reverse power flow, damaging distribution system equipment and negatively affecting reliability of delivery. Then, as PV production wanes later in the afternoon, and as demand increases when people return home, the net demand increases at a much higher rate than offset by PV generation, often resulting in an emergent demand for fast-acting peaking plants. Moreover, this high rate of demand increase often results in voltage and power quality issues, which can be problematic for the utility maintaining regulatory compliance.

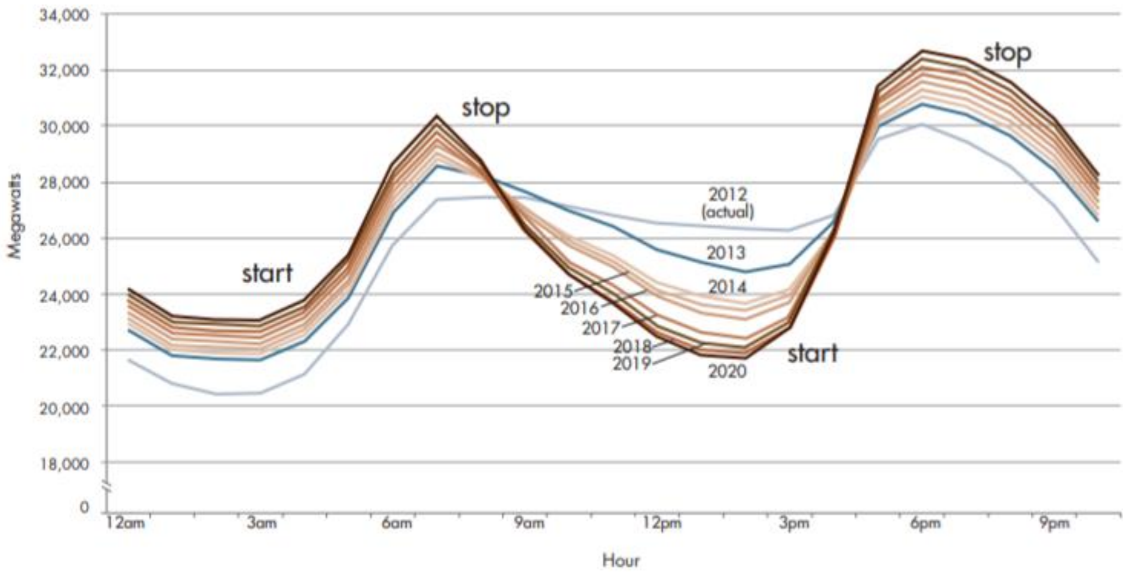

Figure 4. Net Load on January 11 (Source: California Independent System Operator)

Figure 4 shows this demand-generation mismatch which is also known as the "Duck Curve". The figure shows the system load profile in the California Independent System Operation (CAISO) territory on January 11, 2012 and projections for subsequent years. The figure shows various projection levels of the "belly" of the Duck Curve, with each subsequent year showing a lower and lower projected value of net demand. The projected net demand is due to the continued adoption of solar PV within the CAISO territory, relative to load growth (which is stable or declining due to increased efficiency). The combination of increased PV generation and decreasing demand results in a lower belly, which worsens the overall system stability.

The required net generation drop (or load increase) to flatten the duck curve is particularly important. The following solutions can resolve the non-synchronised generation versus demand (duck curve) issue:

1. Curtailing PV production, or
2. Using energy storage to provide base-load services as the penetration of DERs into power distribution systems increases.

The first option, curtailment, is a smart inverter advanced function. However, it is not desirable from a project economics perspective, especially if a third party developer / operator own the asset. Developers determine PV project capacity based upon the revenue they can generate, the negotiated rates that generation is purchased by the utility or other off-takers, and by the available land they occupy. Without appropriate compensation, a change in production capacity through curtailment can negatively influence the project economics. Nevertheless, if the actual conditions dictate the necessity of curtailment, a valuation mechanism is required to evaluate and compensate the asset owner for the lost revenue. While extremely important, the discussion of curtailment value quantification methods is beyond the scope of this paper and will be addressed in a different publication.

Smart Inverter Solution

The second option, using energy storage to provide base load services, can be implemented through the smart inverter function that enables the ability to control charging and discharging. With these capabilities the inverter can be commanded to appear as a load (charging the batteries using co-connected PV or by using the grid if co-connected PV is not available), or as a generator (discharging the energy storage when needed to offset higher demand), resulting in a flattening of the aforementioned Duck Curve. This has a material, economic impact on the system participants, mainly, reduction in the use of non-renewable peaking plants, which are typically more expensive to operate than their renewable counterparts.

The ability to set charge and discharge levels enables a number of valuable use cases, which include:

1. Ramp Rate Adjustment – the capability of smart inverters to set the rate at which their output varies to enable utilities compensate for the high rate of demand growth when PV production wanes (typically late afternoon/early evening). This use case directly affects the aforementioned high ramping requirements present in the Duck Curve example.
2. Price Arbitrage – the ability to charge the ESS at specific times, specifically when prices are low, and discharge the ESS during periods where prices are high;
3. Energy Arbitrage – the ability to charge the ESS at specific times, specifically when energy is from renewable resources, and discharge the ESS during high demand periods;
4. Load or Generation Firming – the ability to smoothen PV generation or load fluctuations so to “firm” the output of the intermittent resource in order to minimize its impact on the interconnected system;
5. Peak Shaving – the ability to prevent excess load from creating a demand peak, potentially exceeding rated capacity of delivery components;
6. Reverse Power Limiting – the ability to prevent excess generation to exceed local demand and cause reverse power flow, potentially damaging distribution equipment;
7. Frequency Regulation – the ability to switch rapidly back and forth between charging/discharging to help stabilize system frequency; and
8. Voltage Profile Management – the ability to interactively maintain and control the voltage profile by absorbing excess generation or releasing power where demand exceeds generation.

Smart inverters can combine all of these cases (within certain constraints) as desired to optimize pricing only, power only, or a mixture of both objective functions. Figure 5 shows a representative use of an ESS performing generation firming from an intermittent PV resource, as well as peak shaving at the circuit level. The top trace (blue) is the PV output; the middle trace (red) is the system output; and the bottom trace (yellow) is the variable consumption of the ESS to absorb the PV energy. The rectangular portion then follows the variable portion, where the PV energy has reduced to zero and the ESS is in full discharge, to support evening peak load demand (peak shaving, possibly price arbitrage, etc.). Note that the PV output in the particular day shown was variable due to cloud coverage. The PV output charged the ESS. The stored energy was used later in the evening to reduce peak load demand. The total view is about 15 hours of generation and load firming.

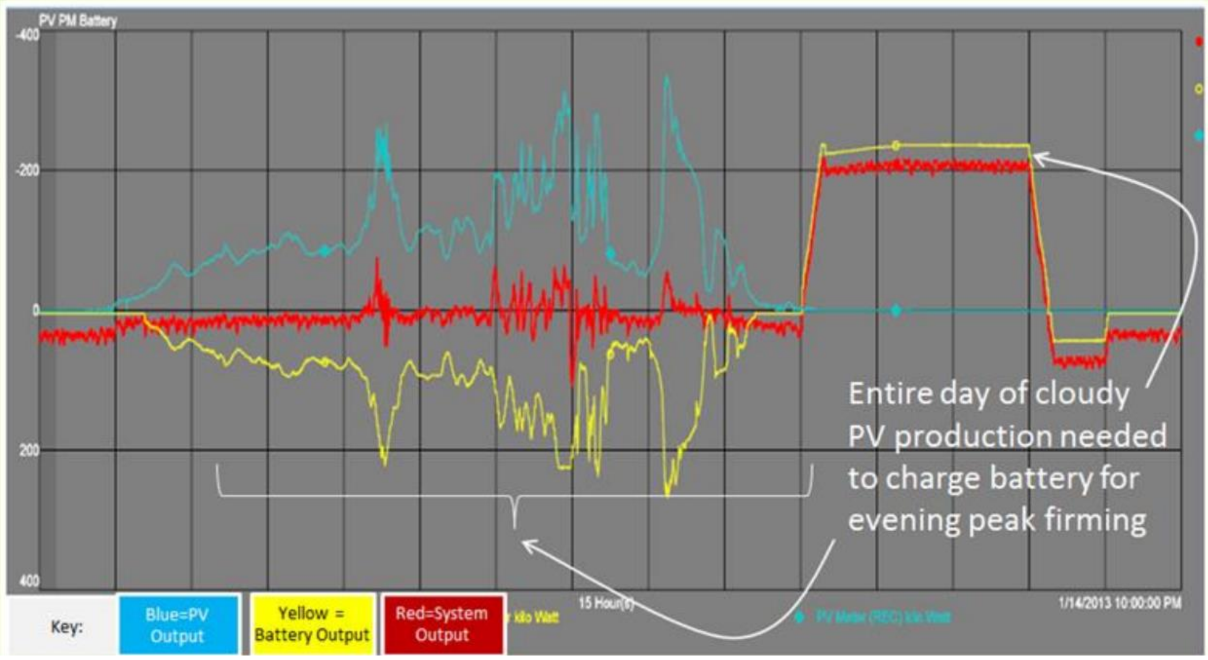

Figure 5. Example of an ESS Performing Generation Firming of an Intermittent Resource Combined with Load Firming of the Evening Demand Peak [6].

It is worth noting that some of these capabilities are advanced functions, in that they require communication between the controller and the inverter as well as knowledge of the capabilities of the inverter asset. These are generally termed "interactive functions", and are distinguished from "autonomous functions".

SMART INVERTER AUTONOMOUS FUNCTIONS

Many utilities throughout North America are quickly developing capabilities to utilize the interactive smart inverter functions, but do not have the necessary communication infrastructure and support systems that enable bidirectional measurement/control. In response to this unavailability, generally, new inverters are delivered with default settings for autonomous operation, specifically the ability to adjust output without a central control system. This is predominantly impacting PV inverters, although all inverters that are installed in the California Public Utility Commission (CPUC) jurisdictional area and Hawaii are required to be certified for interoperability. Other states are evaluating the requirements and are considering their own specifications for interconnection in their territories.
The key intrinsic autonomous functions that can provide value are as follows:

- Anti-Islanding Protection
- Low and High Voltage Ride-Through
- Low and High Frequency Ride-Through
- Dynamic Volt-VAR Operation
- Ramp Rates
- Fixed Power Factor
- Soft Start Reconnection

These autonomous functions are designed to mitigate many localized issues that present themselves at the smart inverter point of common coupling (PCC). Anti-Islanding, which isolates an inverter from the grid and prevents dangerous backfeed during a grid outage, generally is combined with the Soft-Start Reconnection function. Anti-Islanding is considered an "always on" function and is part of the UL 1741 SA certification process. All known utility interconnection agreements (IAs) require a certified anti-islanding capability.

Other autonomous functions are generally configured to be "disabled" unless requested/specified by the host utility as part of the IA. The Low/High Voltage/Frequency Ride-Through functions help stabilize the local grid during periods of voltage transient, and have been developed based upon lessons learned from the unintended consequences of high-penetration solar powered resources in Germany [7]. Volt-VAR curves can prevent over/under voltage at the PCC, and potentially on primary circuits (if enough generation assets are available). Ramp rates control functions are useful during the reconnect sequence, and for compensating intermittent generation (PV, wind) where transient response of the local circuit is poor). Finally, the Fixed Power Factor setting enables reduction of voltage rise due to localized generation, but can be configured off-line (for example: at the time of installation) to provide power factor control.

It is important to note that these autonomous functions are available today, and understanding these capabilities is a key component to broad implementation of smart inverters in the utility ecosystem. Even if utilities may not have the infrastructure in-place to enable interactive communication and control of smart inverters, they may still be able to utilize the full capabilities of the autonomous functions. However, utilities require a comprehensive roadmap for the deployment of inverters with autonomous functions in order to achieve the maximum benefit of using smart inverters.

SMART INVERTER ROADMAP FOR SUCCESS

Smart inverter functionalities can be (and possibly are) technically available in all new inverters. However, utilities have to overcome the challenges that hinder or impede the full realization of the advanced capabilities of smart inverters. The following is a discussion of some of the major challenges:

<u>Evolving Standards and Certifications</u>

UL 1741SA is the current governing standard but does not go far enough for smart inverters. IEEE 1547-2018 standard is approved, but the testing protocols (IEEE 1547.1) are not yet approved or published. Certifications are available today for UL 1741 based on IEEE 1547-2003, but are not available yet for IEEE 1547-2018. Utilities need to consider standards and certification requirements in their jurisdiction prior to sanctioning certain functionalities.

<u>Manufacturer / Certification Body Readiness</u>

In many states, applicable standards are not yet identified and it is unclear if there will be adequate certification facilities that can test and certify inverters to those standards/regulation once ratified. This uncertainty may delay the ability to defer/reduce the need for upgrades, until utilities find reliable sources that can support their needs in terms of manufacturing and testing capabilities.

<u>Back-office Technology Readiness for Integrating Smart Inverters</u>

Utilities need to build the infrastructure necessary to coordinate data capture, communications, cybersecurity, and customer acquisition of data. Without a proper database backbone to support the interconnection requirements such as communication, processing, and data collection, the deployment of smart inverters will not yield the desired outcomes. Stipulating requirements in key areas such as communications, cybersecurity, and public/private networks is still work-in-progress. Requirements need to be finalized in order for utilities to consider the readiness of using smart inverter functionalities as part of normal business.

<u>Impact on Distribution Protection and Distribution Automation</u>

Large-scale deployment of DERs (with smart inverter) will change the distribution network behavior in terms important to the protective relaying system and automatic distribution management. Lessons learned from earlier piloting will help utilities understand the extent of the impacts. Utilities need to consider the potential impacts and be prepared for that.

Need for Assertive/Effective Championship and Support at Corporate Level

Without effective championship and ownership, a large-scale deployment and integration of capabilities of smart inverters may not be successful. Utilities need to understand short, mid and long-term costs and risks associated with implementing or not implementing certain smart inverter functionalities in their system.

Unclear Cost/Consequences of Improper Sequencing in Grid Modernization

If the required support system does not exist, deployment of smart inverters may not yield the highest possible benefits. There is a danger of stranding assets or capabilities if the full solution architecture is not planned thoroughly.

Unclear Boundary Between DERMS and ADMS

DER management systems (DERMS) and Advanced distribution management systems (ADMS) may have conflicting impacts on the distribution assets. Utilities may have different approaches towards DERMS which makes it harder to find a common approach without proper pilot/demonstration projects.

What Portions of Various State Models Should be Pursued?

In California, the Rule 21 Interconnection Tariff [1] mandates CSIP [4], UL 1741SA, IEEE 1547-2018, and IEEE 2030.5 [5]. Hawaii is largely following this approach. Other states have not accepted IEEE 2030.5, but have chosen IEEE 1815 (DNP3). Some utilities have selected vendors, which implement MESA for communication with their storage assets. MESA is not a "certified" model (except by the MESA industry). The bottom line is that following a "do nothing" approach is probably not a viable solution. On another hand, following California Rule 21 or HECO 14 models may also not be the correct path.

Authors presented the above challenges to highlight the questions and uncertainties that need to be addressed in advance before any large-scale deployment of smart inverters is executed. Without addressing these concerns, the risk of not realizing the expected goals can be high. Authors encourage utilities to discuss those issues and determine what approach would minimize the risks and has the maximum potential for success.

The development of a smart inverter roadmap should be an interactive process in which all stakeholders participate. As expected, different utilities may have different priorities based on their client base, their local regulations, and geographical and environmental constraints. Therefore, defining a "one size fits all" solution is not feasible. Benchmarking of existing approaches by other utilities is a reasonable starting point for utilities that are just planning to ramp up their smart inverter DER deployment plans. After benchmarking, there should be an effort to achieve consensus between all stakeholders. Early discussions and collaborations are essential in ensuring that all possible disagreements and differences be resolved in advance, which will pave the way for later success.

REMARKS

The paper identified a number of existing challenges in the deployment of smart inverter DERs, with an emphasis on energy storage resources. The paper also discussed different smart functions and autonomous functions, and presented use-cases for smart inverter DERs.

In this paper, the authors discussed some of the salient features of the smart inverter and the benefits of their widespread deployment. The paper does not intend to provide a comprehensive solution nor does it intend to identify problems, but to provide readers a reasonable background on the most prevalent smart inverter functions and common use cases, from the utilities' viewpoint. Rather, authors identified major challenges questions that must be addressed prior to a large-scale deployment of smart inverters.

Authors acknowledge Mr. David Harris for his valuable contributions to this work.

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