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Review of Impacts and Solutions for Integration of Renewable Intermittent Distributed Generation in Traditional and Future Power Distribution Grids

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SUMMARY

Electric Power Utilities in the US and other parts of the world are experiencing proliferation of Distributed Generation (DG), particularly of intermittent renewable technologies, such as photovoltaic (PV) and wind. This is driven by society environmental concerns, the availability of economic incentives and the need that utilities have to comply with mandates and quotas set by Renewable Portfolio Standards (RPS). The interconnection of DG in distribution grids may lead to important impacts that need to be identified in advance, so appropriate mitigation measures can be designed. The specifics of these impact studies and other related engineering, administrative and policy aspects are usually described in interconnection processes approved by regulatory boards and enforced by utilities. Although noticeable attention has been paid to understand potential short-term issues and outline solutions for integration of intermittent renewable DG in distribution grids, there is still a need for additional focus to identify potential long term issues and the direction the industry should pursue. This includes evaluating the need for updating distribution system design, engineering, planning, and operations practices to accommodate high penetration levels of DG. Evidently, this needs to be accompanied by technology, regulatory, and policy changes that facilitates the evolution of traditional passive distribution systems into active and highly dynamic future distribution grids. This paper: a) reviews impacts and solutions for interconnection of renewable intermittent DG in traditional distribution systems, b) discusses technology, regulatory and policy trends, challenges and needs to facilitate integration in future distribution grids, c) identifies aspects that need to be further discussed and addressed by the industry and government, and d) provides recommendations to accomplish these objectives.

KEYWORDS

Distributed Energy Resources, Distributed Generation, Energy Storage System, Distributed Energy Storage, Impact Studies, Mitigation Measures, Interconnection.

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I. INTRODUCTION

Distributed Generation (DG), also known as dispersed or embedded generation, can be broadly defined as small capacity generation[1] interconnected near demand or consumption centers. DG can be interconnected to transmission, sub-transmission, or distribution (medium and low voltage) grids and has been a subject of study and interest for the power industry for decades. Professional organizations such as CIGRE and IEEE have sponsored numerous committees, working groups, and standards to address the needs of the power industry pertaining to DG integration. The results of these efforts are a set of standards, guidelines, recommended practices, and reports that have been used by utilities and regulatory boards as a reference to define their own interconnection standards and procedures.

Arguably the most prominent efforts in North America are embodied by the IEEE SCC21 Standards Coordinating Committee on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage, the IEEE Smart Grid Interoperability Series of Standards, and above all by the IEEE 1547 Series of Interconnection Standards [1]. The latter consists of a series of standards, guidelines and recommended practices that cover a comprehensive set of aspects pertaining to DG integration, including the IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems [2], which is a key power industry reference in this area. Furthermore, the IEEE Power and Energy Society (PES) has sponsored several working groups to address concerns and needs in this area, including the IEEE Working Group on Distributed Resources Integration [3].

In the particular case of IEEE 1547 the standard was published in 2003 and it set requirements and limitations that were originally envisioned as a means to protect utility grids from potential impacts due to DG interconnection. However, after a decade of business, regulatory and technology developments it required an update to be aligned with current trends and practices in this area. This need was explicitly recognized by the power industry through the introduction of IEEE 1547a [4], IEEE 1547.7 and IEEE 1547.8, which address needs such as voltage regulation and control via DG units, and by the opening of IEEE 1547 for revision [5]. This is an important development, since IEEE 1547 is commonly used by utilities and regulatory entities as a key reference to describe the engineering studies required by interconnection standards and procedures.

II. INTERMITTENT RENEWABLE DG

DG interconnection to the distribution grid represents a challenge for utilities because traditionally the large majority of distribution facilities (substations, feeders, and secondary systems) have been designed to be operated in a radial fashion with unidirectional forward power flows (from the utility grid to customers). Exceptions to this practice are spot networks, secondary networks, and closed-loop/ring systems, which are typically used in high density downtown areas of large metropolis. However, most distribution grids in urban, suburban and rural areas of the US utilize radial feeder operation. DG integration violates this basic assumption and introduces challenges to distribution system design, operations, planning, engineering, and analyses activities.

[1] Here the term small is relative to the system size, for instance DG at transmission and sub-transmission grid level may consist of generation units in the 20 MW to 100 MW (or more) range, while DG at primary (medium voltage) distribution grid level may consist of units in the 500 kW to 10 MW range.

Conventional DG (e.g., reciprocating engines) has been interconnected to distribution grids since the beginning of the power industry and experienced significant interest in the late 70s and 80s as a consequence of the passage of the Public Utilities Regulatory Policies Act (PURPA) in 1978. This type of DG has the advantage of providing a constant, firm, and predictable output, which despite violating the radial operation assumption, simplifies the identification of potential impacts and mitigation measures to ensure seamless interconnection, since the possible number of combinations of feeder loading and DG output conditions can be easily determined and evaluated. Moreover, this type of DG utilizes synchronous machines, which is a very well-known technology for utility engineers.

The last decade has seen the emergence of renewable DG as an alternative to meet societal demands and concerns regarding reduction of greenhouse gas emissions. US distribution utilities are experiencing significant proliferation of renewable DG, particularly of photovoltaic (PV) and wind technologies, which utilize inverters and induction machines for power production, respectively. This is prompted by the availability of economic incentives for renewable DG developers and targets set by Renewable Portfolio Standards (RPS) that utilities are required to attain. These DG technologies have intermittent outputs and are not considered firm generation, given that its primary resource (solar radiation and wind) may not be available when the DG output is needed, e.g., PV generation is not available during nighttime. Intermittent renewable DG causes additional issues due to the variability of its output, which besides leading to challenging distribution grid operating conditions, it can also require of complex planning and analysis approaches.

III. IMPACTS OF INTERMITTENT RENEWABLE DG IN DISTRIBUTION GRIDS

Impacts of intermittent renewable DG in distribution grids are a function of several different variables, including DG installed capacity, DG penetration level (amount of total DG in a feeder relative to its peak load), DG technology (e.g., PV or wind), three-phase or single-phase DG output[2], feeder topology, voltage and grounding, overcurrent and overvoltage protection practices, volt-VAR control and regulation practices, configuration of interconnection transformer, and impedance (or electrical distance) seen from the Point of Interconnection (POI), also known as "stiffness". These impacts on distribution grids can be localized and limited to a rather restricted geographic area, such as those caused by individual utility-scale (MW size) DG, or can encompass larger regions and can even by of system-wide nature, such as those caused by high penetration levels of small-scale DG (e.g., kW size residential rooftop PV) [6], [7].

Intermittent renewable DG impacts in distribution grids can be broadly classified as of steady-state or dynamic/transient nature. Steady-state impacts are typically associated to DG operation under "smooth" output conditions, e.g., such as those observed from a PV plant during a sunny day, and are usually considered as the baseline or starting point for evaluating dynamic/transient impacts. Dynamic/transient impacts on the other side are caused by the variable output of intermittent DG units, e.g., such as that are expected from a wind farm under variable wind speed conditions. Most common DG impacts in distribution grids are described next [8], [9], each one of them has diverse implications that utilities need to consider carefully and that are beyond the scope of this document:

[2] Three-phase DG is common in MW size facilities (utility-scale DG, e.g., a 1 MW plant), while single-phase DG is common in kW size facilities (small-scale DG such as residential rooftop PV, e.g., a 10 kW plant)

- Voltage increase: DG output may lead to voltage increase at the POI and neighbor areas that are above operating limits set by utility standards, e.g., those defined by the ANSI C84.1-2011 standard [10]. This in turn can also lead to complaints from customers, and potentially to customer and utility equipment damage, and service disruption. Figure 1 shows a comparison of feeder voltage profiles (node voltages versus distance from substation) before and after interconnection of a utility-scale PV plant. This example shows that voltage increase may exceed 4% of nominal voltage. For this particular example if the maximum voltage limit allowed by the utility were 1.04 PU, then the interconnection of the PV plant would cause voltage violations at the Point of Interconnection (POI), which is located about 7 miles from the distribution substation, and neighbor nodes.
- Voltage fluctuation: intermittent output from renewable DG can lead to variable power flows and voltage fluctuations at the POI and neighbor areas, particularly for DG interconnected to "weak" distribution grids[3] and/or POIs located far from the distribution substation. If the frequency and magnitude of voltage fluctuations exceed limits imposed by utility standards they may lead to flicker issues, customer complaints, and undesired interactions with voltage regulation and control equipment. Figure 2 shows an example of the effect of PV intermittency on voltages at the POI and how this affects the operation of a voltage regulator located nearby. Under normal conditions (no PV plant interconnection or smooth output profile), the voltage regulator was not expected to change taps. However, the fluctuations caused by PV intermittency lead to voltage excursions out of the regulator's bandwidth for enough time and led to three tap changes in a simulation period of about 30 minutes.
- Reverse power flow: DG output greater than local feeder load may lead to reverse or bidirectional[4] power flow conditions. Depending on the magnitude of DG output and feeder load the reverse or bidirectional power flow can be constrained to a region of a feeder, it can circulate through a feeder breaker and substation bus to neighbor feeders, or it can travel through substation transformers and breakers into the sub-transmission and transmission grids. This can lead to undesired interactions with voltage control and regulation equipment and protection system misoperations.
- Line and equipment loading and losses increase: if the magnitude of the reverse power flow is greater than that of the forward (or normal) power flow then the loading of distribution lines and equipment will be greater when operating in presence of DG. If loading increases beyond maximum operating limits damage to equipment and service disruption may occur. Furthermore, for significant reverse power flow conditions overall feeder losses may exceed those observed during forward (base case) power flow operation
- Power factor decrease: DG units are generally operated by developers at unity power factor to maximize the amount of active energy (kWh) delivered to the grid and billed to the utility. This type of operation implies that DG units will only supply active power (P) to the distribution grid and will not inject or absorb reactive power (Q), or contribute to distribution voltage regulation efforts. Moreover, it implies that the P supplied by the sub-transmission and transmission grids will decrease while the respective Q will remain relatively constant. This leads to an overall decrease of the distribution grid power factor below minimum limits set by some utilities in their contractual agreements with transmission organizations. Finally, this can translate into economic penalties and losses for utilities.

[3] For instance distribution grids supplied by long radial transmission or sub-transmission lines

[4] Bidirectional power flow conditions may vary along the day, for instance, forward (or normal) power flow may be observed during low or no DG output, e.g., during nighttime for the case of PV output, while reverse power flow may occur during high DG output, e.g., during daytime for the case of PV output

- Current and voltage unbalance: proliferation of single-phase intermittent DG can lead to current unbalance, since DG output is injected to only one phase of the grid. This can lead to complex situations where reverse or bidirectional power flow is observed in only one phase while forward power flow still circulates through the remaining two phases. Current unbalance can also lead to voltage unbalance beyond acceptable limits set by utility standards and cause customer complaints and equipment misoperation and damage
- Interaction with Load Tap Changers (LTC), line voltage regulators (VR), and switched capacitor banks: as previously discussed intermittent output from DG units can lead to voltage fluctuations (frequent increase and decrease of voltage along steady-state operating points) that can also trigger the operation of voltage regulation and control equipment such as LTCs, VRs, and switched capacitor banks. It is worth noting that these equipments are designed to monitor feeder voltage and adjust their statuses (e.g., position of tap changers) to keep voltages within predefined targets. However, when voltages change frequently, these devices also operate often in an effort to correct DG induced voltage fluctuations. Since these corrective actions are not instantaneous[5] they can temporarily worsen the operating conditions that they are trying to correct, for instance, by further increasing or decreasing feeder voltages. This can also lead to constant interactions and operations that can also affect equipment life cycle and increase the need for maintenance, which translates into higher capital (equipment replacement) and operating costs (maintenance) for utilities. Moreover, LTCs and VRs operating under Line Drop Compensation (LDC)[6] may be impacted by intermittent DG injection, which can cause the regulation point to shift back and forth due to sudden significant changes in the line current sensed by these equipments
- Reactive power fluctuation: in the particular case of voltage-controlled capacitor banks voltage fluctuations caused by intermittent DG interconnection can lead to frequent switching (off and on operations). This in turn can lead to reactive power fluctuations[7], and further voltage fluctuations and equipment interactions
- Accidental islanding: operation of switching and protective devices can disconnect a region of a feeder containing one or several intermittent DG units from the rest of the distribution grid. If the output from DG units and total load in the electrical island are similar the sustained islanded operation of the DG units may occur. Since existing utility practices do not contemplate this type of operation, accidental or unintentional islanding can represent a safety hazard for utility staff and lead to further operational issues and equipment damage. Therefore, this type of operation is prevented by equipping DG units with anti-islanding protection systems, which enforce detection and automatic disconnection of DG units no later than 2 seconds after accidental islanding occurrence. However, these systems are currently tested under a rather narrow set of scenarios described in UL 1741 [11] and IEEE 1547 standards, and thus are not infallible and may lead to situations where an accidental island operation of DG units is sustained. The power industry has recognized the need to further study this area and propose solutions to address this issue.
- Temporary Overvoltage (TOV): when accidental islanding occurs, the electrical island may lose its reference to ground. If the DG units in the island do not provide a solid reference to ground then voltages may increase significantly and exceed 200% times their

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[5] Utility voltage regulation and control devices are equipped with time delays and bandwidths such as those used thermostats of residential household to prevent frequent operation due to temporary operating conditions and reduce impact on equipment life cycle

[6] LDC is a common distribution voltage regulation practice whose objective is to maintain voltage constant at a point downstream of the LTC or VR, for instance, a large or critical customer load. This is attained by measuring the line current through these equipment, using it to estimate the voltage drop along the line, and adjusting tap positions to compensate for it

[7] Capacitor banks inject reactive power to the distribution grid, and frequent switching on and off operations are seen as reactive power (Q) step changes by distribution substations and sub-transmission and transmission grids

nominal value. This can damage utility and customer equipment, e.g., arresters may blow, and cause service disruptions.

- Impacts on overcurrent protection systems: interconnection of intermittent renewable DG can lead to impacts on overcurrent protection systems, these impacts are a function of the DG technology, fault current injection[8], and configuration of interconnection transformers and distribution feeder (four wire multi-grounded Y, three wire ungrounded delta, etc). Some of the most common impacts encompass sympathetic tripping, reach modification, protection coordination misoperation, including nuisance fuse blowing.
- Harmonic distortion: power electronic equipments such as PV inverters introduce distortions into the power grid in the form of harmonic current injections. Although these equipments need to comply with standards such as IEEE 1547 and IEEE 519-2014 [12] that limit individual harmonic injections, the aggregated effect from hundreds or thousands of inverters is difficult to predict. The end result may either be the cancellation or addition of individual harmonic injections, being the latter an undesirable scenario that can lead to harmonic distortion levels exceeding those allowed by industry standards and can cause service disruptions, complaints or economic losses from end users, particularly those relying on the utilization of sensitive equipment for critical production processes.
- Voltage sags and swells: sudden connection and disconnection of large intermittent renewable DG and fault current contribution to faults may lead to short duration and infrequent voltage variations also known as sags (voltage decrease) and swells (voltage increase). These voltage variations can cause the tripping of sensitive equipment of end users and cause service disruptions and economic losses
- Voltage and transient stability: voltage and transient stability are well-known phenomena at transmission and sub-transmission system level but until very recently were not a subject of interest for distribution systems. However, as intermittent renewable DG proliferates situations were voltage and transient stability are a concern are becoming more common, examples include voltage stability limits of long distribution lines, such as those typically found in rural areas, with high proliferation of DG, and tripping of DG units due to voltage and frequency disturbances caused by contingencies at bulk power system level. The latter has been recognized as a critical issue by the power industry, given that under contingencies such as loss of large bulk generation blocks, support provided by DG units may help maintain system stability, and tripping of these units may worsen the effects of the initial contingency. In order to address this issue, the power industry is currently working on updating and developing new voltage and frequency ride-through standards, beyond those already discussed in IEEE 1547, and requiring DG technology manufacturers to include this feature in their products. Notable efforts in this area include those led by NERC [13], [14].

[8] For instance, fault current contribution from PV DG is usually 110% to 130% times its nominal current

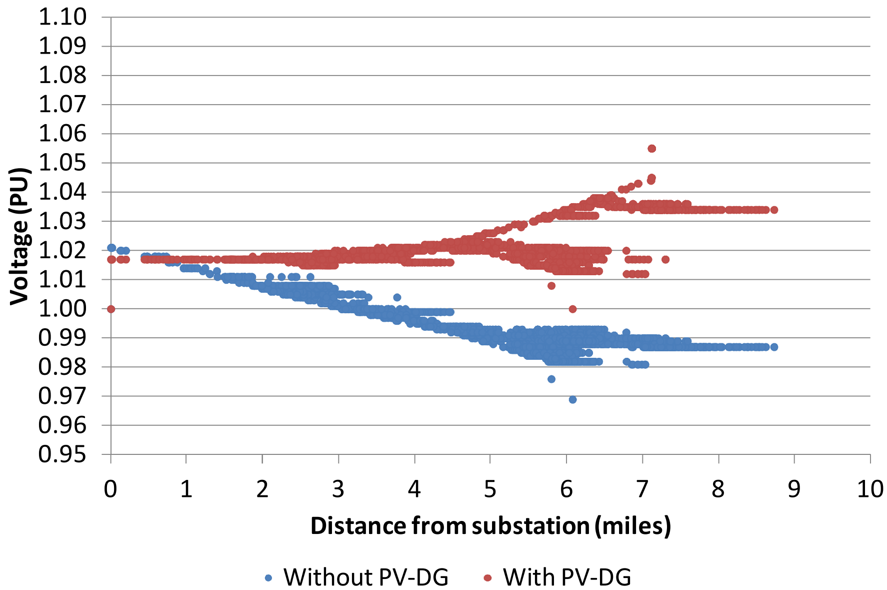

Figure 1 - Impact of DG on Feeder Voltage Profile

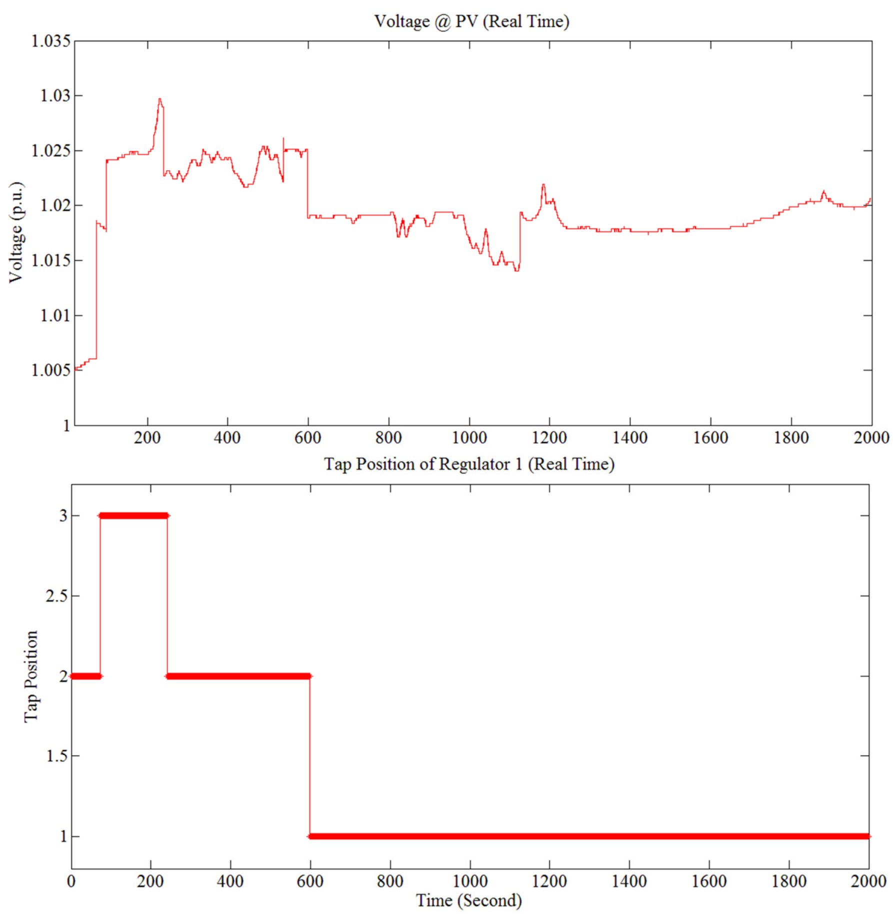

Figure 2 - Impact of DG on Voltage Fluctuation and Operation of Line Voltage Regulator

As previously indicated the severity of these impacts is a function of multiple variables, particularly of the DG penetration level. However, generally speaking it is difficult to define reasonably accurate guidelines to determine maximum penetration limits of DG or maximum hosting capacities of distribution grids[9] without conducting detailed studies. Utilities and regulatory board across the country have attempted to tackle this complex subject by defining heterogeneous limits either as a function of aggregated DG capacity, or feeder penetration level, which is the ratio of installed DG capacity versus daily (or daytime) peak load. Some utilities are evaluating these penetration levels by feeder and making them available to developers. A notable example is Hawaiian Electric Company (HECO), which has made available up-to-date Locational Value Maps (LVM) for the island of Oahu that show the DG penetration levels of their feeders as a function of peak load and daytime peak load. It is worth noting that these LVM maps are updated on a daily basis [15]. Moreover, California IOUs have also made this type of information available [16], [17], [18]. This information may be used as a reference to identify potential interconnection locations. For instance, feeders with high DG penetration levels are expected to be more prone or susceptible to further impacts caused by interconnection of additional DG. Since costs of mitigation measures needed for seamless DG interconnection may be allocated to developers, it is likely that they will choose to interconnect new plants to feeders with low DG penetration levels, where impacts are less likely to occur or their severity is less grave. This solution is itself an effective mitigation measure.

IV. MITIGATION MEASURES AND SOLUTIONS

Impacts caused by intermittent renewable DG interconnection are addressed via a variety of mitigation measures. The purpose of mitigation measures is to alleviate impacts and ensure seamless integration of DG units. Mitigation measures include conventional solutions and advanced or smart grid solutions [19]. Conventional solutions encompass relocating or modifying settings and operation modes of voltage control and regulation equipment, setting DG units to absorb reactive power [20], reconfiguring distribution feeder systems, and building express (dedicated) feeders for large DG interconnection, among others. Smart grid solutions include implementing dynamic volt-VAR control utilizing DG units, limiting or curtailing the output of DG units, utilizing advanced protection systems such as Direct Transfer Trip (DTT), distribution class FACTS devices, and Distributed Energy Storage (DES).

These solutions have advantages and disadvantages related to their effectiveness, implementation complexity, and costs, being advanced solutions more complex and expensive to implement, but also more effective in alleviating severe impacts. For this reason, conventional solutions are generally suitable for solving simple and moderate impacts such as those usually found in low DG penetration levels, while advanced solutions are reserved for complex and severe effects that are more common in high DG penetration levels.

Since PV is the predominant technology being deployed in distribution systems and inverters are a key component of this type of intermittent renewable DG units, a solution that is particularly attractive due to its cost-effectiveness and flexibility is the utilization of smart inverters. Smart inverters are power electronics devices that besides the basic function of DC to AC conversion found in conventional inverters also include advanced features such as reactive power injection and absorption, dynamic volt-VAR control, voltage and frequency regulation (commonly known as “grid forming” capability), active power curtailment, voltage

[9] Maximum amount of DG that can be interconnected to a distribution feeder

and frequency ride trough, two-way communications, etc. All these additional features and capabilities facilitate the implementation of individual and coordinated mitigation measures to alleviate local and system-wide impacts of intermittent renewable DG. For this reason the power industry, and particularly utilities in the West Coast, represented by the Western Electric Industry Leaders (WEIL) Group[10], are actively advocating for the utilization of smart inverters as a vital component of distribution systems of the future and enablers for further integration of intermittent renewable DG [21]. On the technical side, the Rule 21 Smart Inverter Working Group (SIWG) sponsored by the California Energy Commission (CEC) has played a key role in increasing awareness about the advantages of this technology and its potential benefits for system operations and intermittent renewable DG integration [22].

Although engineering solutions, such as smart inverters, are available for mitigating a large variety of impacts, utilities are constrained by technology costs, standards and regulatory practices. For instance, dynamic voltage control of distribution feeders utilizing intermittent DG units, which is conceptually similar to that used in sub-transmission and transmission grid operation, is still not allowed by most utilities. This despite the fact that the technology required for its implementation is already available, being the main limitation existing utility practices, which are constrained by standard and regulatory barriers. The power industry and IEEE have recognized this need and is currently addressing this specific subject as part of its IEEE 1547 series of standards. On the technology cost side, although DES is clearly one of the most effective mitigation measures, since it also provides additional operational flexibility and the ability to fully exploit the potential benefits of intermittent DG, it is also the most costly of the solutions. Therefore, if high penetration scenarios of intermittent renewable DG are envisioned, further support and work is needed to address these aspects (standards, regulatory, utility practices, and technology costs) and facilitate a wider adoption of advanced mitigation measures.

As previously discussed Energy Storage Systems (EES) is a very effective and flexible, although expensive, solution to mitigate impacts and facilitate seamless integration of high penetration levels of intermittent renewable DG. Among the large variety of energy storage technologies, Battery Energy Storage Systems (BESS), is arguably the most commonly utilized for this type of application. This type of technology has the advantage of being modular and having four-quadrant operation capability, which means that the same facility can operate under any of the four possible combinations of active and reactive power absorption and injection, providing additional versatility for voltage regulation and control applications. Distribution applications of EES can be of utility-scale (MWh size) or highly distributed (kWh size) nature. The effectiveness of this solution to mitigate impacts is a function of its location, being in general more effective when installed close to intermittent renewable DG units. Besides its suitability to mitigate impacts, it also enables some of the potential benefits of intermittent renewable DG.

Some of the most common potential benefits of distribution applications of combined ESS and intermittent renewable DG[11] include output smoothing, "firming up", and intentional islanding of DG units, distribution system capacity deferral, energy arbitrage, and frequency and voltage regulation. Output smoothing consists of setting the EES in such a way that the combined output of the intermittent renewable DG and ESS facility remains relatively

[10] WEIL members include leaders of some of the largest IOUs in the country, such as Southern California Edison (SCE) and Pacific Gas and Electric (PG&E) http://www.weilgroup.org/members.html

[11] It is worth noting that ESS can also be utilized independently, i.e., in applications where no DG units are available. Most of the benefits described in this section are still valid for independent applications of ESS. Examples of this applications are reported extensively in the literature http://energystorage.org/energy-storage/applications-energy-storage-technology

constant along the day, regardless of primary resource (solar radiation or wind speed) variations. This can be accomplished by charging the ESS when the DG output exceeds a predefined threshold and discharging it when the DG output falls below this limit. Firming up is related to output smoothing and consists of using the ESS to guarantee a combined output of the ESS and DG facility regardless of primary resource variations. This is particularly useful when combined with "grid forming" PV inverters in intentional islanding applications, where it is necessary to know with certainty the amount of generation (in this case provided by the combined output of ESS and DG units) available to supply the load of the electrical island. This is very important in microgrid applications, where the combined Distributed Energy Resources (DER)[12] in the island are expected to be self-sufficient during islanded operation. It is worth noting that microgrid applications of this sort are seeing growing interest in the power industry as a means to improve grid resiliency and reliability during and after major events such as severe storms and hurricanes. Distribution system capacity deferral consists of utilizing the combined (and already "firmed up") output of ESS and DG units to decrease the load served by distribution assets (substation transformers, feeder lines, etc) that otherwise would be overloaded and need to be replaced by new capital investments. Here firming up is vital to ensure that the combined ESS and DG unit output will be available when needed. Energy arbitrage consists of charging the ESS when energy is less expensive and discharging it when it is more costly, i.e., in layman terms "buying cheap and selling for a profit". Finally, frequency and voltage regulation applications utilize the combined output of ESS and DG units to provide support to the transmission and distribution grid during contingency or normal operating conditions to keep frequency and voltage within limits set by utility standards.

Utility-scale EES are usually installed at distribution substations, feeders, and DG locations. This type of solution is typically considered as a suitable alternative for mitigation of complex impacts and interaction effects caused by high penetration of utility-scale intermittent renewable DG. Highly distributed DES on the other side is usually located closer to end-user facilities and is a more suitable solution for mitigation of impacts caused by high proliferation of small-scale intermittent renewable DG and other emergent technologies such as Plug-in Electric Vehicles (PEV) [25], [26]. A well-known application of this technology is the Community Energy Storage (CES) concept introduced by American Electric Power (AEP), which consists of highly distributed small (25 kWh to 75 kWh) pad-mounted BESS installed in parallel with conventional distribution transformers [27]. The introduction of the CES, advances in power electronics based distribution transformers, and the fact that intermittent renewable DG technologies such as PV generation, as well as Plug-in Electric Vehicles (PEV), operate with DC, has prompted proposals for utilization of DC distribution at low voltage level. This is an area of growing interest that requires further attention by the power industry and US government.

It is worth noting that the application of EES to mitigate impacts of intermittent renewable DG in distribution systems is still relatively uncommon. This is due to the fact that ESS is an economically and technically recommendable solution to mitigate complex interactions and impacts typically associated with high penetration levels of intermittent renewable DG, which not all distribution feeders or substations have attained yet. This means that for low to moderate DG penetration levels other mitigation measures may be enough to alleviate impacts and facilitate integration. However, as proliferation levels increase and get closer to (or exceed) maximum hosting capacities of feeders and substations, the need for advanced mitigation measures such as ESS may grow as well. This has been recognized by the power

[12] DER in this discussion refers to DG, DES and demand response

industry already, for instance, California passed the first energy storage mandate in US history in October of 2013, which requests IOUs to install 1.3 GW of ESS by 2020 [28]. Furthermore, HECO is currently in the process of requesting proposals for EES with total capacity ranging between 60 MW and 200 MW to facility operation of its grid under high penetration of intermittent renewable DG [29].

If proliferation of intermittent renewable DG achieves or exceeds the levels observed in some areas in California and Hawaii, there would be a growing need to utilize ESS not only to mitigate impacts and facilitate integration, but most importantly to take advantage of the potential benefits of DG, such as those described previously. This would need to be accompanied by a review and update of distribution system design, engineering, planning, and operations practices, and wider adoption of real-time monitoring and control technologies. This is an area where further industry and government action is certainly required to incentivize innovation and research and development of potential solutions.

V. CHALLENGES AND TRENDS

Intermittent renewable DG is still an area of study for the power industry, and several challenges still remain. Some of these challenges are of very technical nature and their discussion is beyond the scope of this document, others are strategic in nature and have business, regulatory and policy implications. The latter include fundamental questions such as: what is maximum penetration level of renewable intermittent DG that the industry is expecting to achieve? Is the industry willing to shift the paradigm from exclusive reliance on large centralized generators and long transmission lines, to a scenario where they coexist with high penetration levels of DG (conventional and renewable), and where the latter plays an important role in supplying demand? Is this technologically and economically feasible or even desirable? What is the "optimal" balance between centralized generation and DG? Should it be left to market, regulatory and policy-making forces to define that balance, or should the industry take a proactive leadership and planning role in this discussion? Recent evidence seems to indicate that for some utilities either the balanced or high DG penetration scenarios are being considered or mandated through regulatory rulings as potential alternatives [23], [24]. For instance, California's Assembly Bill No. 327 passed on October of 2013 explicitly states:

> *"This bill would require an electrical corporation, by July 1, 2015, to submit to the commission a distribution resources plan proposal, as specified, to identify optimal locations for the deployment of distributed resources, as defined. The bill would require the commission to review each distribution resources plan proposal submitted by an electrical corporation and approve, or modify and approve, a distribution resources plan for the corporation. The bill would require that any electrical corporation spending on distribution infrastructure necessary to accomplish the distribution resources plan be proposed and considered as part of the next general rate case for the corporation and would authorize the commission to approve this proposed spending if it concludes that ratepayers would realize net benefits and the associated costs are just and reasonable".*

Under these scenarios there is an evident need to update distribution system design, engineering, operations and planning practices, how should this distribution system of the future look like? What should be the role of DES, microgrids, and other emergent technologies and concepts under these scenarios? Answering all these questions require participation from all industry stakeholders. Utilities, regulatory boards, state and federal policy makers, and customer advocacy organizations will certainly play a vital role. Moreover, manufacturers, professional, academic and research organizations, and consultants can also contribute.

VI. CONCLUSIONS AND RECOMMENDATIONS

The power industry is largely focusing on solving short and midterm impacts introduced by proliferation of intermittent renewable DG, particularly by utility-scale units. This is being done by assuming that the distribution grid equipment and planning and operations practices will remain largely untouched, and fixes or restrictions will be introduced to facilitate DG integration. This approach does not address the fundamental cause of the problem, which is the fact that distribution practices were not envisioned for a highly active and dynamic grid with bidirectional power flows and significant penetration levels of DG. A few leading utilities are dedicating efforts to solve this fundamental question and propose alternative engineering designs, e.g., close-loop operation of distribution feeders [30], [31], [32], [33], planning, and operations practices for the distribution system of the future. There is an opportunity for such system to consider DG, either intermittent or conventional, as an intrinsic component and shift the focus from mitigating impacts or restricting proliferation to fully exploiting their potential benefits, including improved efficiency and reliability, for instance via the implementation of intentional islanding and microgrids. Intentional islanding under the microgrid concept refers to utilizing DG units (conventional and/or renewable) along with other DER, such as DES and demand response, and advanced distribution automation, communications and control technologies, to intentionally sustain the operation of an electrical island after it has been disconnected due to a contingency on another part of the grid. Islanded operation under the microgrid concept can significantly improve customer reliability by ensuring continuous operation during emergency conditions, such as major storms. Successful utility experiences have been reported in the literature and media, including a recent outage restoration experience at San Diego Gas and Electric (SDG&E) Borrego Springs Microgrid facility [34]. This is an area of growing interest, which is part of the power industry's system resiliency efforts.

The operation of such a complex, dynamic and active distribution grid may require not only alternative engineering designs, planning, analysis, and operations practices but also wider utilization of modern protection systems, including a shift from traditional approaches such as extensive fusing in favor of advanced protection and automation technologies such as those used in subtransmission and transmission grids. Furthermore, modern voltage regulation and control technologies are needed, this may include a combination of centralized and distributed controls, the widespread adoption of smart inverters, and the introduction of faster and continuous voltage regulation and control equipment. The latter capabilities are provided by distribution class FACTS devices and power electronic-based equipment, which are suitable to address DG driven intermittency issues and replace traditional technologies such as step-voltage regulators and switched capacitor banks, which provide slow and discrete (stepwise) voltage regulation and control. It is worth noting that some of these technologies already exist [35], [36] as solutions for specialized applications. Further development and experience with similar types of solutions is needed for adoption at larger scales such as those envisioned in high DG penetration scenarios. Moreover, extensive utilization of advanced sensors, including Phasor Measurement Units (PMU) [37], real-time monitoring, automation and control, and more effective utilization of existing AMI infrastructures, may be needed to increase system visibility and facilitate real-time operation. This is likely to require additional developments in communications, information and enterprise systems and infrastructures, to be able to gather, process, and analyze large amounts of data. High proliferation and reliance on intermittent renewable DG would also require significant attention to detailed and accurate distribution system modeling, simulation, and analysis[13], and especially to DG output forecasting. The latter will require thorough gathering and analysis of solar radiation and wind speed patterns and the development of new (or upgrade of existing) computational tools, information systems, and techniques. This will enable the utilization of intermittent renewable DG in daily (very short term) operations and planning activities. Finally, operating this type of dynamic and active distribution system is likely to require: a) the adoption of operation practices and systems similar to used in subtransmission and transmission systems, were very-short and short term forecasting and operations play a critical role, and b) a more closely coordinated operation of transmission and distribution systems. Therefore, more advanced and integrated Energy Management Systems and Distribution Management Systems (DMS) are likely to be required. All these areas require further support and action by the power industry and government to incentivize innovation and research and development of pertinent solutions.

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