Grid Edge Technology as a Non-Wires Alternative

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***Abstract*—Megatrends such as rapid adoption of Distributed Energy Resources (DER) such as roof-top solar PV, lithium ion battery storage technology and electric vehicles is changing the paradigm of utility infrastructure. In addition to operating an aging infrastructure and/or load demand increase, utilities need to find new philosophies and methodologies for managing their conventional precepts of maintaining reliability, resilience and good quality of supply to consumers in addition to supporting these new technical challenges that impact the grid head on. Sheer reliance on medium voltage (MV), slow, electromechanical solutions such as load tap changers, switched capacitor banks, line voltage regulators, or line upgrades will not help utilities to manage all problems associated with these fast-moving trends. In recent times, a new distributed grid-edge power electronics technology has shown promise for utilities called the dynamic var compensator (DVC). This technology resides on the secondary side (Low Voltage LV) of service transformers and can help utilities manage fast voltage fluctuations under changing load trends and help with voltage optimization in addition to preserving the fundamental requirements demanded from the grid. This grid edge technology can be used by the utilities as a cost-effective Non-Wires Alternative (NWA) to achieve deterministic flexible control over their system without the need for consumer participation. This paper through several case studies and field experiences highlights the use of this grid edge technology as a new resource in every utility's toolkit.**

***Index Terms*—Non-Wires Alternative (NWA), Volt-VAr control (VVC), Volt-VAr Optimization VVO, Conservation Voltage Reduction (CVR), electric distribution system, grid-edge, distribution automation**

I. Introduction

Traditionally, when distribution utilities have had a need to upgrade or replace infrastructure due to aging equipment or increased load, they would simply conduct poles and wires projects that could earn a regulated rate of return. In recent years with a dramatic reduction in price of solar panels and associated balance of system, there has been a proliferation of distributed energy resources (DER) at residential and C&I scale especially in states like Hawaii and California [1][2]. Utilities and regulators look to explore the use and deployment of DER technology to address infrastructure needs at a lower cost with higher customer, utility and environmental benefits.

Further, the cost of lithium ion batteries has reduced due to economies of scale. Many vendors today offer a battery storage solution that can provide residential customers emergency back-up power during outages, or if coupled with PV installation, the battery storage system can be charged during the daytime with the excess generation from PV and the stored energy can be used during peak hours in the evenings when the cost of electricity is higher in a time-of-use pricing structure. This changes the way electricity flows on the grid, as compared to the conventional model of a one-way flow of electrons from the generation plants to consumers. Consumers are now becoming prosumers. This requires a change in operational and planning philosophy for utilities to manage their distribution network.

Another trend that is disrupting the way electricity is consumed on the distribution grid is penetration of electric vehicles (or even plug-in hybrid electric vehicles) [3]. Several car companies today offer a cost competitive alternative to an internal combustion engine-based counterpart. Consumers have started gravitating towards electric vehicles due to its technological appeal, in some cases due to its environmental benefits and in some cases due to sheer economics. Generally, EVs are charged by residential consumers during night-time or at their workplaces. If the penetration of EVs increases beyond a certain threshold, utilities will need to upgrade service transformers, secondary conductors, and even substation power transformer and; primary conductors and cables to support the increasing demand. This causes a dramatic shift in energy usage pattern from what we see today.

In addition to managing these new trends, utilities are still faced with the conventional challenges of maintaining reliability, managing voltage levels to be within the ANSI-A limit during normal operation, and providing an excellent quality of supply to consumers. Furthermore, several utilities today have mandates to host a certain level of DERs on their system as per Renewable Portfolio Standard (RPS), some other utilities have mandates to conserve a certain percentage of energy and capacity year over year, while some others are interested in reducing and shaving peak demand during extreme weather conditions [4][5].

Managing the ever-changing nature of grid dynamics while preserving the fundamental precepts becomes a daunting task for utilities. Especially, when most of these new trends bring along with them increased voltage fluctuations, and variable flow of electricity much different from what conventionally has existed on the distribution grid. Current technology that exists on the grid such as capacitor banks, line voltage regulator or line upgrades and is readily available to the utilities in most cases cannot handle these changes and requires utilities to perform costly upgrades.

New power electronics-based grid-edge technology offers promise to manage and mitigate some of the problems that accompany these fast-moving trends and can be classified as a Non-Wires Alternative (NWA) to conventional upgrades or solutions using MV VVC assets. This new grid-edge technology comprises fast acting voltage regulation mechanism to mitigate the effect of dynamic voltage fluctuation, to fix the voltage issues at the lowest nodes on the feeder, and to manage voltage across the feeder to be within the ANSI-A limits. These aspects of the grid edge technology ultimately help to unlock many different applications in the distribution network. The idea is that the utility deterministically controls the grid edge technology that is completely owned by them without reliance on consumer usage patterns.

This paper through several real-world case studies an field experience presents the various applications of power electronics-based grid edge technology as a non-wires alternatives (NWA) that allows utilities to successfully achieve their conventional objectives, even in the presence of fast-moving trends such as adoption of PV, EV, and battery storage.

II. Power Electronics Based Grid Edge Technology

In recent years, power electronics based distributed grid-edge technology has revolutionized grid control on distribution network. Grid edge devices are generally utility-owned single-phase devices rated at around 10 kVAr and operate on the secondary side of the service transformers (208V, 240V, 277V). They are usually placed at the locations on distribution circuit that require support (over-voltage or under-voltage). A group of these grid-edge devices operate autonomously and regulate the local voltage tightly at a specified setpoint within a specified dead-band (±0.5V). Grid edge devices can be series connected or shunt connected. The shunt connected flavor of these devices are called Dynamic VAr Controllers (DVC) [6][6]. The shunt connected devices not only regulate the secondary voltage but positively impact the primary side of the distribution network due to VArs that flow on the primary side and compensate for excess VArs that would otherwise results in technical losses. An example of shunt connected grid edge device installed either on a pole or pad is shown in Figure 1. All these devices are capable of two-way wireless communication with either a hosted or an on-premise server that hosts a grid edge management software application that acts as the supervisory control, provides visualization, and data analytics on the data collected from all the field deployed devices

Fig. 1. Pole mounted (left), pad mounted and integrated designs (center) and software platform for the grid edge DVC technology

III. Multiple Distribution Network Applications of Grid Edge Technology

As highlighted in the introduction, proliferation of PV, EVs and battery storage on the distribution system, especially when adopted by residential customers, leads to a plethora of challenges for the utility to manage. This section provides several interesting applications through real-world examples of deployment of grid edge devices on the distribution system as NWA that would enable utilities to manage these new impending problems while achieving their conventional objectives. Alternative solutions using grid edge devices are considered in combination with MV VVC assets to address service voltage issues while optimizing the regulated rate of the return.

A. Capital Expenditure (CAPEX) Deferral

Voltage optimization on the distribution network is the process of optimally managing voltage across the feeders to be within the ANSI-A band during normal conditions (and ANSI-B band during emergency peak conditions). Planning engineers use conventional technologies such as load tap changers (LTCs), capacitor banks and line voltage regulators (LVRs) to achieve this objective. After making a certain recommendation comprising, for instance, placing / moving / replacing capacitor banks (fixed or switched) or LVRs at different locations on the grid, a cost versus benefit analysis is run to choose the best solution with the higher benefit to cost ratio.

1) Case Study 1: Deferral of New Regulators

A handful of grid edge devices can instead be used in place of an LVR on the grid to provide not just support, but near real-time visibility, and speed of response that is much faster than electromechanical equipment such as LVRs or Cap Banks to support the new trends on the grid.

As grid edge devices are shunt connected and small-rated, they can be distributed and deployed at locations that need support. Therefore, the deployment of LVRs can be deferred, (indefinitely in some cases). For instance, consider the voltage profile (voltage versus distance) on the left in Fig. 2 from an actual utility. It is found that phase A (red) has a deep voltage drop on one of the branches and potentially requires a single phase LVR to fix the problem. However, if we place 9 DVCs, then the voltage is improved by 2% under peak load (right plot). These 9 locations now provide visibility in addition to voltage support. In terms of cost, this is a competitive solution than having an LVR and it offers many more benefits beyond simple voltage regulation.

2) Case Study 2: Optimized MV and LV Solution

A second succinct example from a different utility demonstrates the value of grid edge LV technology in conjunction with MV assets for optimizing the voltage of a long distribution circuit. Further, through this example it will be clearly demonstrated that a combination of LV and MV technology can prove to be more cost effective than just using primary MV upgrades.

The circuit considered for this analysis has an MV voltage of 12.47 kV with 3.2 MW peak and a maximum length of 13.3 miles. It has 384 service transformers (93% are pole-mount).

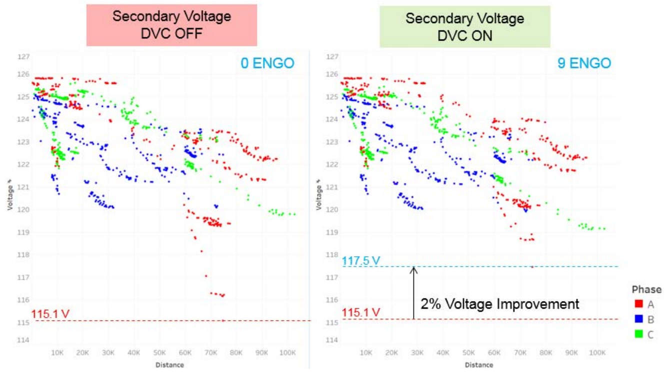

Fig. 2. Voltage profile (left) without any grid improvements shows low voltage on phase A (red). With 9 DVCs, the low voltage is improved by 2% (right) and the need for an LVR is deferred.

The substation has a feeder head regulator (FHR) with a setpoint of 122.5V ± 1.25V (R=5, X=3). Further, the feeder has two line-voltage regulators (LVRs) and two primary capacitor banks with a total capacity of 1,800 kVArs.

The voltage profile of the circuit (voltage versus distance plot) under peak load is shown in Fig. 3. The figure also highlights the locations with lowest voltage showing 103.5V under peak.

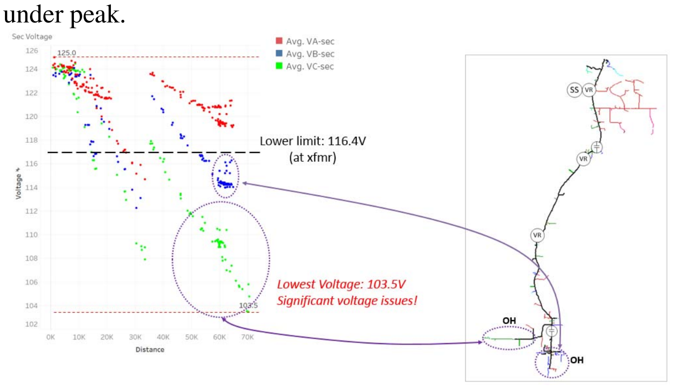

Fig. 3. Voltage profile without system improvements shows 103.5V minimum voltage at the end of the feeder

With an optimized deployment of primary MV assets that entails adding 2 x 600 kVAr switched cap banks, upgrading a 600 kVAr fixed bank to 1,200 kVAr fixed bank and modifying the LDC control of the LVRs to R=6, X=2) and adding 30 DVCs (LV assets), the minimum voltage of the system can be improved by 15V to 118.5V under peak (see Fig. 4). This is a significant improvement in voltage and alleviates all voltage problems on the system at the minimum cost. To emphasize, the utility performed an independent analysis by just upgrading and adding MV assets and the cost of the solution was found to be twice the cost of the combined MV+LV optimized solution.

3) Case Study 3: Deferral of Service Transformer Upgrade

Let's consider another example from an actual field deployment. A transformer rated at 37.5 kVA is overloaded and sees a high voltage drop causing voltage to drop below 114V (see left side of Fig. 5). Adding a second 10 kVAr shunt connected DVC on the same transformer pushes the voltage up by 1.67% and relieves some VAr loading on the transformer. The installation of the DVC does not require a line outage and takes only 30-45 minutes to install. This low-cost solution allows the utility to defer the upgrade of the transformer for a few more years without impacting the quality of supply of their customers nor planning an outage.

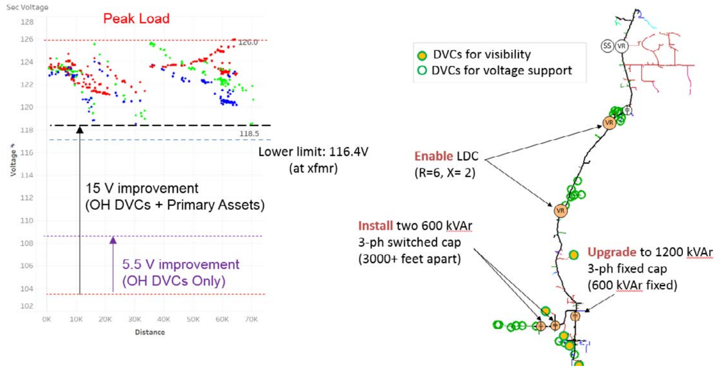

Fig. 4. With an optimized MV+LV solution, the voltage is improved by 15V and the minimum voltage rises to 118.5V even under peak

These DVCs have been finding such applications with several utilities where the cost of deploying DVCs tends to outperform the cost of conventional upgrades and the benefits from DVCs far supersedes what conventional solution can offer in terms of visibility.

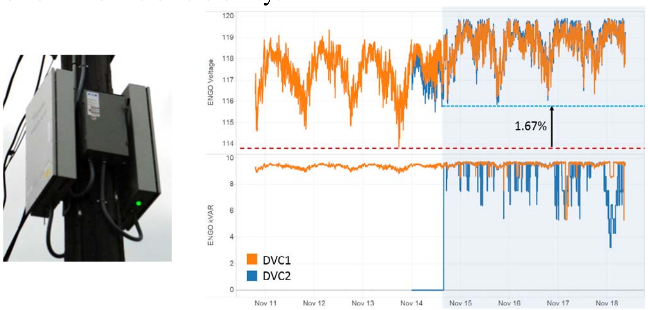

Fig. 5. Transformer voltage (orange) shows low voltage due to overloading. With the installation of a second DVC at the same transformer (right), the voltage is improved by 1.67% and transformer upgrade is deferred

B. Mitigating Flicker and Power Quality Problems

As the DVC is a power-electronics based device, it can respond within one cycle to mitigate flicker caused due to C&I loads turning ON and OFF such as irrigation motors, grain bin drying facilities, saw-mills etc. Flicker can cause nuisance for residential customers who are on the same feeder due to the nasty C&I loads that exist on the feeder. Two different examples are presented in this section that show different philosophies of using the DVCs to manage flicker.

1) Case Study 1: Mitigating Irrigation Motor Load Flicker

In the first example, a 100 HP motor that operates at 460V connected to a 75 kVA single phase transformer that has a center tapped secondary voltage of 480V (240V – N – 240V). Two DVCs are connected between the center tapped transformer. The philosophy of using a DVC on such applications is to directly mitigate the problem at the source of it and prevent the flicker from travelling on to the feeder. As seen in Fig. 6, without the DVC, a flicker of more than 5% is observed. While, the DVC cuts down the flicker to less than 2%.

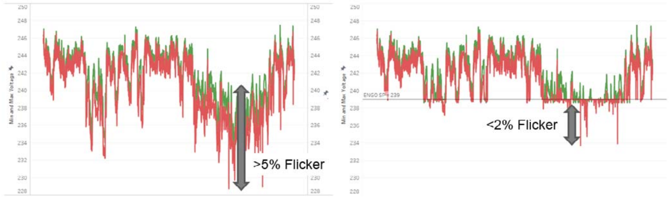

Fig. 6. A 5% flicker due to a 100 HP motor is observed at the transformer without any fast voltage support (left). Two DVCs connected across the transformer reduce the flicker to 2% due to fast sub-cycle response (right)

2) Case Study 2: Mitigating Feeder Wide Flicker

A second philosophy of using DVC is to mitigate flicker by locating the DVCs not at the source of the problem but where the flicker causes nuisance on residential customers in the vicinity. For instance, in situations where the size of the C&I load causing issue is large (MWs), the DVC will need to be placed on different locations on the circuit to provide a shield to residential customers from the flicker.

Fig. 7. shows an example of a voltage profile where a feed mill is connected close to the substation and when the feed mill turns ON it causes a 5% voltage flicker on the entire feeder downstream of the substation. With 114 DVCs deployed, the voltage flicker on the entire feeder is limited to 0.3% - 2.5%. This distributed solution of DVCs is less expensive and more competitive than STATCOMs or DVARs connected on the MV side that require maintenance, suffer from a single point of failure, require large space and have high installation and commissioning cost. In this case study, the DVC that existed upstream close to the substation was not performing well and had to be decommissioned.

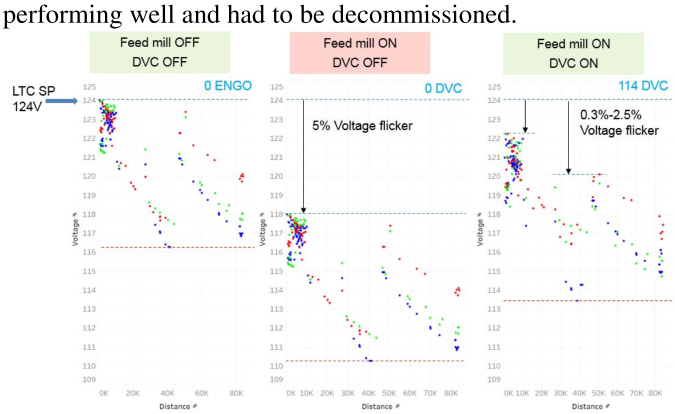

Fig. 7. Without any MV or LV support and with the feed mill off, minimum feeder voltage is around 116V (left), as soon as the feed mill turns on, the minimum voltage on the entire system drops by 5% (center). 114 DVCs reduces the flicker to less than 2.5% (right) to isolate all residential customers

C. End-of-Line Voltage Sensing

As DVCs have the capability of monitoring voltage in near-real time they can be used as End-of-Line sensors (EOL) for urban circuits that are tightly coupled and have short lengths. This would be of interest to utilities without AMI infrastructure but are interested in performing CVR for peak demand reduction for instance. An integration of the central grid edge management software (that controls all the DVCs with the ADMS or D-SCADA VVO engine that controls the primary assets would provide a closed-loop operation). The VVO engine would read the voltages recorded by DVCs every 15 minutes and take action related to lowering LTC setpoint voltage to achieve demand reduction. This is a simple yet a powerful application of DVCs. Around three (3) DVCs per feeder can provide tremendous value to the utility on such circuits. Several pilot projects with DVCs have demonstrated the power of EOL sensing using DVCs in achieving peak demand reduction.

D. Increasing PV Hosting Capacity of Distribution Circuits

As discussed before, DVCs can act within a cycle to mitigate voltage fluctuations. On circuits with high residential PV, the problem of voltage fluctuation is distributed and difficult to manage using MV assets. DVCs offer a unique solution to this distributed problem, wherein utilities can deploy DVCs at will on a circuit to reduce the voltage fluctuation caused by cloud cover variation. Through several pilot deployments in Hawaii, the value of DVCs to double and even triple the PV hosting capacity of a distribution network has been demonstrated. Once the voltage variation across the entire feeder is reduced using DVCs, then the LTC setpoint at the substation can be lowered to create an upper voltage headroom as shown in Fig. 8. This upper voltage headroom enables hosting more PV without causing upper voltage violations. The PV hosting capacity increase obtained from the four field deployments of around 146 DVCs in Hawaii is provided TABLE I. .

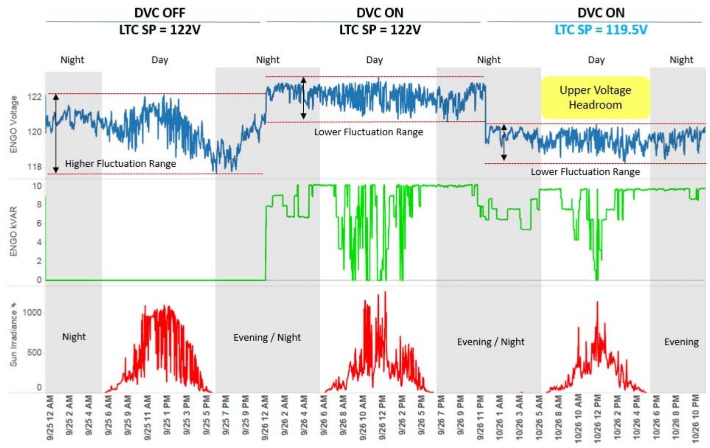

Fig. 8. Top plot – Secondary side voltage, Middle Plot – VArs injected by DVC to support the voltage, Bottom Plot – Solar Irradiance. i) left most part shows a day when DVCs are OFF not injecting VArs and only measuring voltage, ii) middle part shows a day with DVCs turned ON injecting VArs to support voltage, iii) right part shows a day with LTC SP lowered and DVC turned ON with a lower SetPoint

TABLE I. PV HOSTING CAPACITY INCREASE ACHIEVED WITH DVCS ON FOUR SUBSTATIONS ON THE ISLAND OF OAHU, HAWAII

Sub	#Feeders	Peak Load (MW)	Daytime Min Load (MW)	Present Solar MW	PV Pen w/o DVC	# DVC Deployed	PV Pen w/ DVC
A	2	6.3	2.34	4.8	76%	61	147%
B	2	6.2	3.5	4.4	71%	38	231%
C	1	3.2	1.65	1.0	31%	30	84%
D	1	2.17	0.67	1.77	82%	17	135%

E. Energy Savings and Demand Reduction

Several utilities have a mandate to save energy generally in the range of 2% - 4% using CVR. As AMI becomes ubiquitous, more voltage issues are becoming evident on the distribution system. Therefore, it becomes difficult for the utility to achieve their energy savings targets without fixing these voltage problems first. It has been found that by just fixing 3% - 5% of the nodes on the distribution network, the utility can reap benefits associated with voltage reduction for the entire system. As the nature of these issues are distributed, a solution like DVC is well-suited for fixing these problems.

Similarly, many IOUs are also interested in reducing their peak demand during extreme weather conditions. Generally, there are a few nodes that prevents the utilities from maximizing reduction of the voltage. At the same time, there are smaller distribution utilities such as Coops, that are interested in reducing their demand charges and perform CVR to achieve demand reduction during peak times. These Coops have an incentive to reduce their demand charge levied by their G&T. Again, by fixing a few nodes on the system, a large voltage reduction potential can be created.

By deploying an average of 4 DVCs per average MW, a voltage control of up to 6% can be achieved for Energy Savings and/or Peak Demand Reduction application.

F. Generation and Transmission Benefits

In a recent project with large utility, the use of distributed grid edge technology for Generation and Transmission support was tested and demonstrated. Operating Generation and Transmission (G&T) network effectively is a complex undertaking for independent system operators (ISOs) and utilities. Transmission congestion forms a major concern for ISOs that may require expenditures on the order of millions of dollars per year to alleviate the problem. Further, extreme weather events add to the cost with emergency load reduction that may be difficult to manage with centralized systems and can negatively impact customers. In addition, voltage stability on G&T network is controlled by devices like DVCs and STATCOMs today that suffer from a single point of failure. A novel bottom-up approach to these problems wherein 681 DVCs were deployed on 47 feeders across the distribution network of the utility company operating in two states running off a single transmission corridor to reap multiple benefits of emergency peak demand reduction, voltage stability, dynamic VAr management, all with deterministic control within the hands of the utility without negatively impacting the customers. The savings far supersede the cost of the distributed grid edge technology that provides a resilient and reliable system for achieving multiple G&T objectives in addition to local voltage support.

The results of the testing for the utility in one state with 5 substations and 23 feeders and 351 DVCs yielded results shown in TABLE II. Further, it was computed that if an emergency peak demand reduction was performed for all 5 substations, with MV and LV assets, a voltage reduction of 7.68% (taking ANSI-B as the threshold) can yield a savings of 6.45 MW or $188,826 in savings. This is tremendous savings in addition to flexibility in supporting VAr management and upstream voltage support without a single point of failure that supports the vision of any utility to maintain resilience and reliability of their network.

TABLE II. KEY PARAMETERS COLLECTED IF ALL SUBSTATIONS PARTICIPATED IN THE TESTING

Parameter	Value
MW Increase / Decrease	3.6 MW
Max. lagging/leading MVAr Control	11.3 MVAr / 7.6 MVAr
Weighted Avg. %Voltage Margin without / with DVCs	2.34% / 4.35%
Peak MW & MVAr (non-coincidental)	110 MW, 15.3 MVAr
Measured avg. CVR Factor for Power	0.75
Number of DVCs	351

IV. CONCLUSIONS

In conclusion, this paper highlighted the use cases and strengths of grid edge technology as non-wires alternatives through many case studies and field experiences gained over the past several years. As rapid changes in utility landscape driven by aging of the distribution infrastructure, proliferation of roof-top solar PV, battery energy storage devices and electric vehicles alters the philosophy of operating and planning the grid, new technologies such as the one presented in this paper become imperative as a part of the utility toolkit. The availability of fast acting power electronics technology deployed at the edge holds promise for utilities to tackle the growing challenges of uncertainties that can be only managed if utilities had full flexible control over these new assets without over reliance and complete knowledge of consumer habit and participation. Utilities have conventionally enjoyed deterministic and complete control over the grid and these new grid edge technology options provide utilities with tools that can future proof their system while preserving their fundamental requirements of reliability, resilience and excellent quality of supply to their consumers.

ACKNOWLEDGMENT

We would like to thank all our utility customers who have, through pilot projects and eventually commercial deployments, enabled us to show the value of this new grid edge technology for use as a Non-Wires Alternative.

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