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Field Trial of Power Electronics LV Power Regulators in a Utility Distribution System

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SUMMARY

Delivery of reliable, cost-effective electric power services is the core mission of local distribution utilities. This misison is becoming more challenging as policies encouraging the broad adoption of distributed energy resources, such as solar PV, push the bounds of well-established engineering rules and practices. Distribution engineers increasingly need to be able to contend with distributed and variable generation and load conditions for which traditional solutions are not sufficient.

Advances in power electronics based systems make it possible to develop products that can play a significant role in migrating to a more flexible and resilient distribution system that can simultaneously respond to distributed, dynamic events, while achieving the cost and reliability levels expected by end customers. A new class of power regulator device based on power electronics, designed for use in the low voltage (LV) secondary portion of the distribution system, offers a multi-function capability for managing power by providing dynamic voltage regulation, reactive power compensation, and harmonic cancellation to counter the new distributed energy challenges.

This paper provides a summary of a field trial with this new power regulator deployed in the local distribution utility environment at Greater Sudbury Hydro. The objectives of the trial are to demonstrate real-time, continuous voltage regulation in a field deployment, define key integration points between the power regulator and the distribution management and operations systems and to understand the relationship between this new technical capability and overall economic benefits. The paper describes motivations for investigating the use of power regulators in the distribution grid, highlighting solar PV integration and Volt-VAR Optimization (VVO) as initial applications. The technical operation and performance characteristics of this new class of power regulator are explained in some detail. Results of load flow modeling and other prepartory steps, including integration planning, and acceptance testing are briefly summarized, highlighting lessons learned and key results. Field performance results for the power electronics based LV power regulator are reported and compared to the models and to the project objectives. Implications of the device performance on system operations and opportunities for future work are also discussed.

KEYWORDS

Power Electronics – Distribution - Field Trial - Regulator – Low Voltage – Secondary – Solar PV – CVR – VVO – Volt Var Optimization

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1. INTRODUCTION

The delivery of reliable cost-effective electric power services is the core mission of local distribution utilities. The engineering approach to manage this mission is based on well-established rules and methods that assume uni-directional power flow for a defined set of topologies and predictable customer load patterns. But, a number of key input factors have changed dramatically in recent years. Government policies mandating integration of renewables in significant levels, generation capacity constraints, and energy efficiency initiatives require utilities and their system vendor partners to innovate in order to continue executing the core mission.

Power electronics based in-line power regulators (IPRs), scaled for use in the low voltage (LV), secondary portion of the distribution grid, represent one such innovation. IPRs provide multi-function capability for managing power, with dynamic voltage regulation, reactive power compensation, and harmonic cancellation closer to specific loads.[1] Power electronics devices are not entirely new to the electric power grid, having been used in Flexible AC Transmission System (FACTS) and High Voltage Direct Current (HVDC) transmission systems. Similarly, distribution utility-owned and controlled LV IPR actuation systems integrate into existing communications and Supervisory Control and Data Acquisition (SCADA) systems, participating in the management of feeder circuits and providing visibility at grid edge. The purpose of this field trial is to validate these capabilities as a step toward building a more flexible and resilient, cost-effective, reliable distribution system.

2. MOTIVATION AND OBJECTIVES

2.1 Regulatory Environment

The Ontario Energy Board (OEB), the regulator of all Local Distribution Companies (LDCs) in Ontario, established the Smart Grid Working Group in 2011 under provisions of the Energy Act. The Working Group accepted the work of the Ontario Smart Grid Forum in establishing provincial objectives based on three main areas: Customer Control, Distribution System Flexibility and Adaptive Infrastructure, as shown in Figure 1.

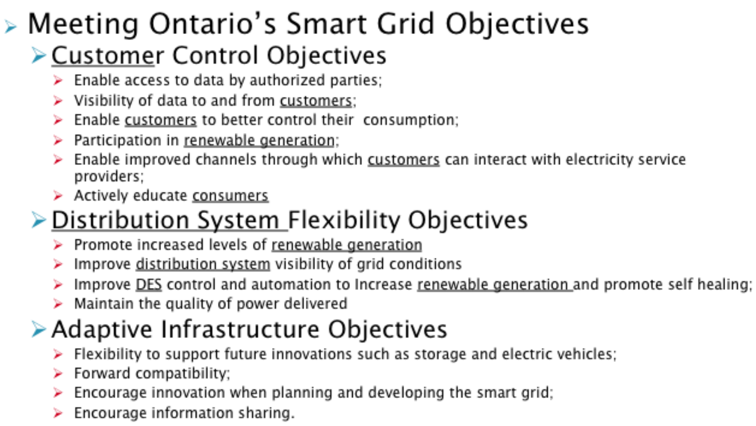

Figure 1. Ontario Smart Grid Objectives

The Electricity Act also establishes key statutes defining high level requirements for implementing the Smart Grid, as follows:

1. The grid will accommodate all generation and storage options (Electricity Act, Section 1.3a).
    a. Will focus on photovoltaic generation (PV) - solar panels.
2. The grid will motivate customers to be an active grid participant and will include them in grid operations (Electricity Act, Section 1.3b).
3. The grid will optimize its assets and operate efficiently (Electricity Act, Section 1.3c).

2.2 GSHI Distribution System Vision

Within the Greater Sudbury Hydro Inc. (GSHI) distribution system, investments in Advanced Metering Infrastructure (AMI) and SCADA have improved visibility (to one hour and several seconds, respectively), making strides toward meeting the objectives and delivering on the smart grid mission. Distributed generation has been rising including Combined Heat and Power (CHP), landfill gas generation and Photovoltaic (PV) Solar, with some feeders experiencing reverse power flow more than 80% of the time. Over the next five years, the vision for this distribution system is to:

- Integrate AMI data in system operations and planning;
- Use Smart Inverters for sub cycle voltage and harmonic control – local autonomous control;
- Maintain the Geographic Information System (GIS) in near real time;
- Add many more sensors feeding data to SCADA;
- Utilize utility grade, inverter based or stand-alone “power conditioners” that control voltage, power factor and harmonics - used for voltage regulation, and Volt Var Optimization (VVO),
- Install more automated switches on the distribution stystem.
- Evaluate and utilize adaptive relaying as it becomes available.
- Introduce operator support tools Distribution Management System/Distributed Energy Resource Management System (DMS/DERMS).

These initiatives all support increased penetration of distributed generation, energy storage and engagement with customers as we move toward grid parity. GSHI needs new technologies of which first and foremost is local, autonomously controlled solutions at the edges of the distribution system. It is within this environment that GSHI is evaluating the power electronics LV power regulator.

2.3 Field Trial Objectives

The primary objectives for the power electronics LV IPR field trial are to deploy a device on the secondary voltage system that can autonomously regulate voltage, improve the Distributed Energy System (DES) power factor and mitigate harmonics, in particular at locations that have high penetrations of distributed PV generation, energy storage or demand response. The trial also demontsrates the ability to integrate device controls with the existing GSHI SCADA system using open protocols, such as DNP 3, and provides visibility and the potential for control of DES assets.

3. APPLICATIONS: SOLAR PV INTEGRATION AND VVO

3.1 Mitigating the impact of High PV Penetration and Intermittent Power

Among the potential technical impacts of high levels of solar generation on a particular feeder circuit, over-voltages and intermittent voltage variations greater than 3% are both concerns. [2] Power export conditions, or reverse power flow, will tend to drive up secondary voltage for customers behind the corresponding distribution transformer. Additionally, if these variations are large enough to effect voltage on the primary MV line they will tend to drive regulating equipment, particularly voltage regulators, to actuate frequently, reducing the asset lifetime. While LV IPRs do not directly alter the nature of PV power generation, they can be leveraged to reduce the negative side effects. In the secondary distribution system, the IPR can buck voltage rise associated with reverse power flow situations, and counteract rapid swings maintaining a stable voltage for customers.

3.2 Volt Var Optimization

As mentioned in section 2.2, VVO, including CVR programs, is part of the near term vision at GHSI. Achieving Peak Reduction and Energy Efficiency (EE) objectives with a VVO implementation means, as Figure 2 shows, both primary and secondary parts of a given feeder will need to be modified from their current state. Earning the benefits of a VVO program fundamentally come down to being able to manage voltage within a reduced portion of the ANSI standard (+/- 5% vs. nominal 120 V), specifically the lower 6-7% of the 10% total range.

Techniques for managing and regulating the primary voltage are well known, generally involving regulation equipment at the substation and out on the line. Historically, these devices have operated independently, with an overall response time of several minutes. This control approach works reasonably well for many feeders when the goal is voltage control to 5 or 6%, but getting to 3-4% is more challenging. If all the Peak Reduction or EE were to come from just improved primary management, the range would likely need to shrink to 2% or less. This degree of primary voltage control would be difficult and expensive to achieve, especially factoring in distributed energy sources.

If the voltage near the point of service can be boosted, the primary voltage can be lowered and the customer is still assured compliant voltage. If the voltage near the point of service can be dynamically regulated to a specific voltage, then the delivered service voltage becomes completely independent of the primary voltage. As shown in Figure 3, IPR-based voltage assurance makes sense where the incidence of an atypical secondary voltage drop coincides with a low voltage point on the primary feeder. Regulating the LV side at this point reduces the effective secondary engineering standard to about 2.5% (3 V) or less. Even though there may only be a handful of locations that require voltage assurance, they are a real constraint on VVO savings, if left uncorrected.

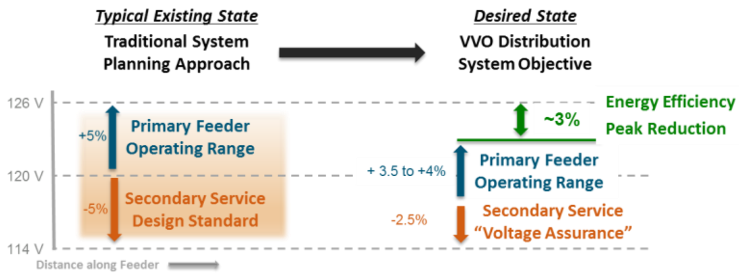

Figure 2. Achieving VVO Objectives means modifying primary and secondary operating voltage range standards

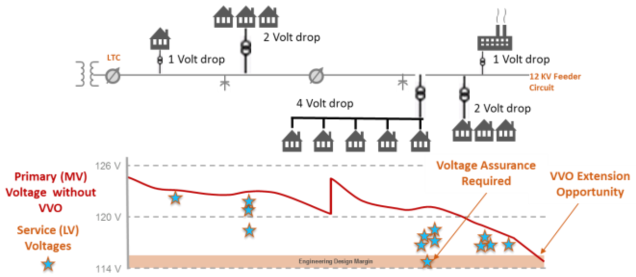

Figure 3. Voltage Assurance and VVO Extension are two mechanisms for using the regulating capability of LV IPRs to generate feeder level Peak Reduction and EE.

Based on the applications defined in sections 3.1 and 3.2, and on the practical requirements for deployment in the outdoor plant environment at GSHI, a set of technical requirements have been established for the IPR, as summarized in Table 1.

4. LV POWER REGULATOR DESIGN AND FUNCTION

The IPR design is based on the shunt/series device architecture, implemented as a Unified Power Flow controller (UPFC) and shown in Figure 4 and described in [1]. This device captures both the benefits of a STATCOM and DC/AC Voltage Source by combining the relevant section of each and tying them together at a common DC bus. This architecture affords the versatility of being able to improve load power factor, source additional Vars for feeder level support, regulate voltage over a wide range (eg. ±10%) and filter out voltage harmonics. The same architecture can be used to develop single phase or three phase products, but for this trial a 50kVA, 240 V low voltage (LV) single phase design was chosen. The "shunt side" of the device, essentially a static synchronous compensator (STATCOM) uses its ability to source or sink reactive current (Vars) into the inductive components of the distribution transformer and the utility feeder conductor to improve load power, mitigate harmonic currents or regulate voltage. In practice, in this particular implementation we choose not to use the "shunt side" for voltage regulation since technically, this stage is not truly a "local" voltage regulator due to the fact that the injected current has voltage impact on all nodes, with the local node just being the largest. This aspect can sometimes be advantageous, but can also cause unintended coupling and

Table 1. Technical requirements for a 50 kVA pole-mounted IPR for use in high PV secondary and VVO/ CVR distribution applications

1-Ph 50kVA Pole-Mounted IPR Requirements	
Phase	**Single, L-L**
Rating	**50 kVA**
Form	**Standalone Pole Mount**
Cooling	**Passive (air)**
Frequency	**60 Hz**
Operating Temperature	**-40° to +50° C**
Source Voltage	**240 VAC Nominal**
Source Voltage Range	**-30% to +25% of Nominal**
Load Voltage Regulation	**Boost/Buck up to ±10% of Nominal; ±0.5% accuracy;**
VAr Compensation Range	**10% of rating, leading/lagging**
Harmonic Correction	**3rd to 15th, odd order;**
Harmonic Distortion	**Voltage THD < 3%** **Current TDD < 5%**
Efficiency	**≥ 99%**

interaction with the entire feeder [3]. Instead a series oriented voltage source, the "series side" is used to regulate voltage. This stage of the device uses DC/AC converters to buck or boost the AC voltage either directly or through a step down transformer connected in series with the load. The power handling capability of the converter is a function of the voltage regulation range. This means this technique can regulate the output voltage over a range of ±10% with only 10% of the full load power rating. This capability enables the same device to mitigate high penetrations of residential PV on a secondary and/or participate in a VVO energy savings program.

The device was tested against the requirements of Table 1 prior to implementation in the field. Figure 5 shows the basic voltage regulating characteristics of the IPR as part of the test plan, In this case, it is clear that the device maintains the regulation setpoint of 240 V nominal over a broad range of input voltages. This performance has also been compared to an ideal Local Voltage Regulator (LVR) [1].

5. INTEGRATION AND DEPLOYMENT DESCRIPTION

Figure 6 provides the overall feeder circuit topology and the detailed configuration within the secondary distribution network, prior to installation of the IPR. The IPR is installed in series between the distriubution transformer and the customer sites, three of which have 10 kW rooftop solar PV. Figure 7 shows the schematic plan and overhead polemount deployment position for the IPR and its controller. The installation includes additional monitoring equipment for ongoing P, Q studies. In the final field configuration, the IPR was postioned opposite the distribution transformer on the pole, but this is not a general requirement.

The total circuit distance for GSHI 20F1 feeder is just over one mile. The feeder has a peak load of about 1.6 MW and serves a mix of residential, commercial and industrial customers. Although the three PV solar arrays, each have a nameplate rating of 10 kW, these can be expected to generate about 25 kW at peak output. The distribution trnasformer has a 50 kVA rating. Given the expected peak loading, the medium voltage (MV) primary profile was found to be relatively flat, with a total voltage drop of 1-2 V, using commercial load flow models. In addition to the static load flow models, we also developed a PV model for the secondary system, using an intermittent PV generation model.

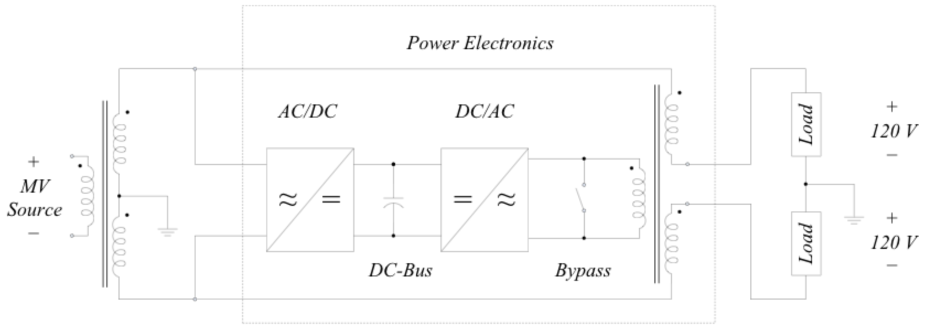

Figure 4. UPFC architecture of the power electronics in line power regulator.

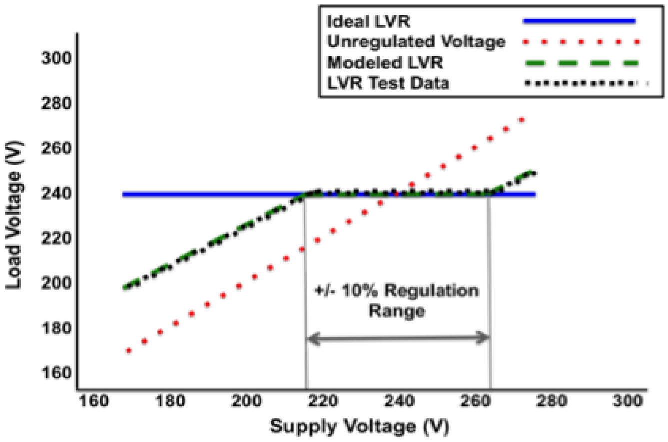

Figure 5. Lab test results validating regulating characteristic of the LV IPR.

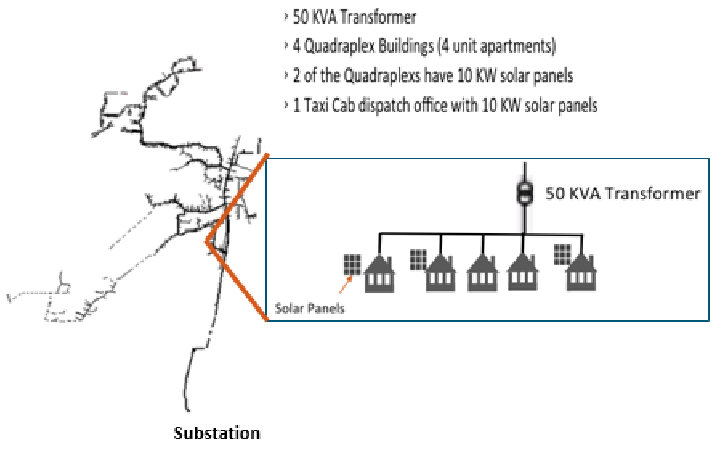

Figure 6. An overview of the feeder circuit topology and the secondary detail prior to the IPR trial.

In addition to the physcial connection of the IPR in series with the distribution transformer, the IPR controller or DGC (Distributed Grid Controller) was integrated with the GSHI SCADA system via a serial connection. Pre-testing of this capability confirmed that the device would be able to share data and alarm information with the SCADA system. Figure 8 provides SCADA views of the new distribution topology with data output display from either the power quality monitors or the IPR's onboard monitoring system. The availability of this type of data from the IPR on an ongoing basis provides more visibility at the grid edge for GSHI operations teams.

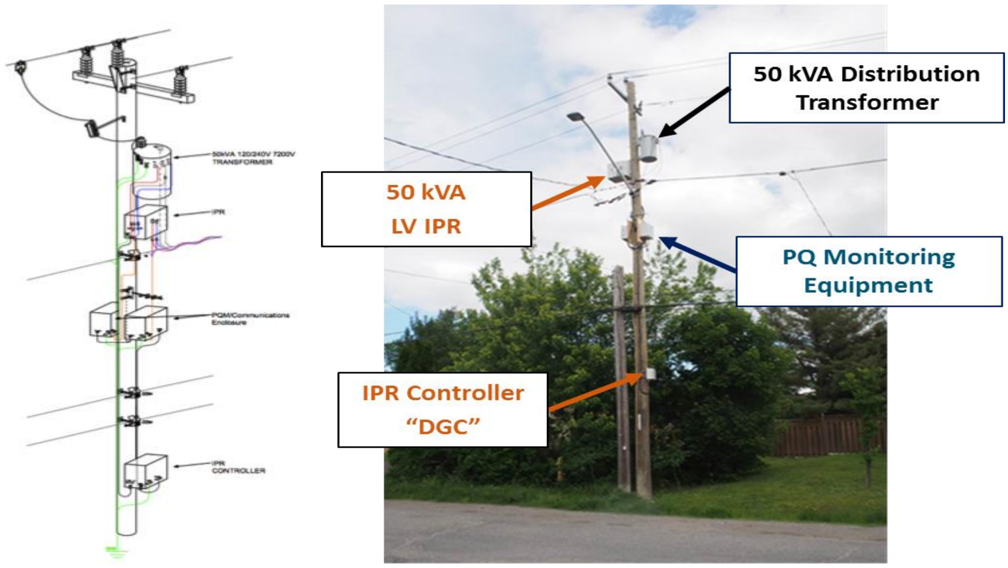

Figure 7. This drawing shows the planned configuration of the in-line power regulator (IPR) and controller with the distribution transformer and communications lines shown (left). In the final installation (photo, right), site-specific adjustments were made and the IPR was mounted on the opposite side of the pole from the transformer.

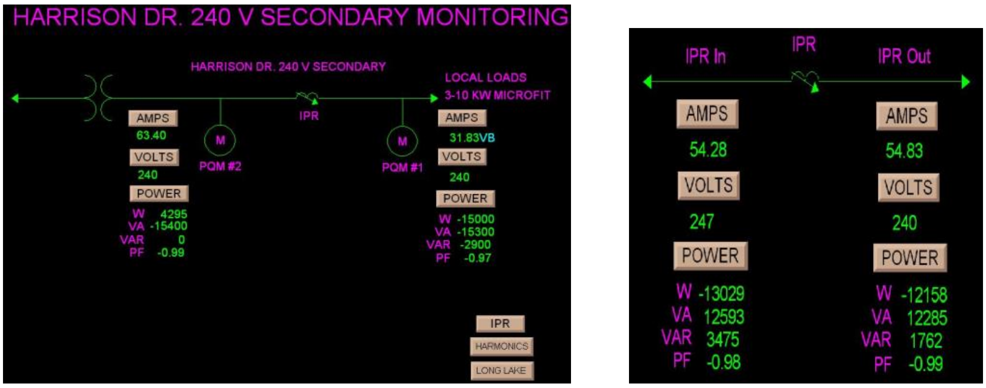

Figure 8. The screen shot to the lift shows PQ readings for a case with the IPR output voltage and input voltage both being equivalent at 240 V and the IPR providing 2.5 kVAR. In the right half of the figure, the data from the IPR's onboard monitoring system show that the device is regulating a 247 V input voltage to the setpoint of 240 V and providing a fixed 2.5 kVAR.

6. FIELD DATA AND OBSERVATIONS

A 48 hour data capture snapshot is provided in Figure 9, showing the IPR input voltage level (output voltage from the 50 kVA distribution transformer), regulated voltage and real power flow. The two days were charcterized by intermittent clouds, which led to highly variable PV power production. The combined 30 kW nameplate systems generated more power than was needed at times for local consumption, exporting power to the main feeder. This reverse power flow is significant near solar noon. The IPR was set to regulate voltage to 240 V, and miantained this voltage throughout the measurment period. This behavior is consistent with the device modeling and acceptance testing results. The device has also demonstrated its ability to provide VAR support to the system, but active power factor correction will be activated later in the trial which is scheduled to continue through much of 2014.

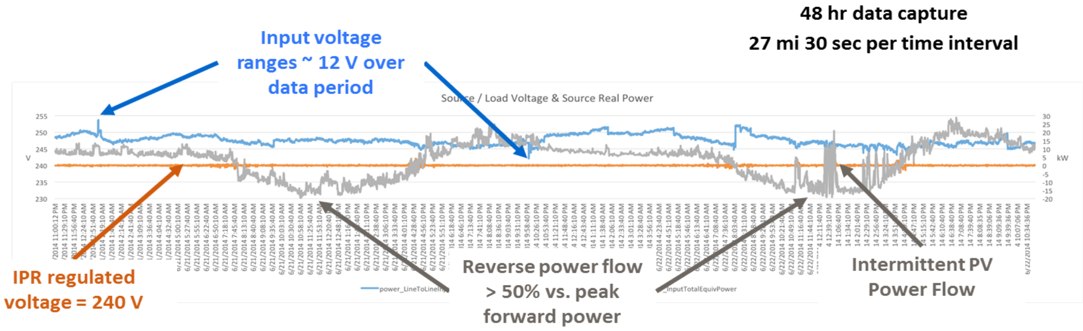

Figure 9. A data snapshot showing source voltage (blue), IPR output (load) voltage (orange) and power flow (gray). The y-axis scale to the left is voltage and the IPR setpoint is 240 V. The scale to the right is real power flow. During the highest solar production time of each day, the secondary ciruit has reverse power flow of more than 50% of the higest daily load. The power electronic based IPR is regulating voltage consistently throught the entire period.

7. DISCUSSION AND NEXT STEPS

The trial is demonstrating the potential for this new power electronics based technology. Modeling and analysis has supported the development of the device and the overall trial planning. LV IPRs can regulate voltage to a controlled setpoint, even in a secondary distribution environment with highly variable PV generation and large reverse power flow. The device has also demonstrated the capability to inject a fixed VAR level into the system. The trial will include turning on power factor control in addition to voltage regulation. In addition to demonstrating how such a device could be used by GSHI to step closer to the smart grid vision while delivering compliant voltage to all customers, we are also developing the economic framework to determine the overall value for enabling increased levels of PV, as well as participating in advanced VVO programs.

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