Methods to Determine Recommended Feeder-Wide Advanced Inverter Settings for Improving Distribution System Performance

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***Abstract* — This paper describes methods that a distribution engineer could use to determine advanced inverter settings to improve distribution system performance. These settings are for fixed power factor, volt-var, and volt-watt functionality. Depending on the level of detail that is desired, different methods are proposed to determine single settings applicable for all advanced inverters on a feeder or unique settings for each individual inverter. Seven distinctly different utility distribution feeders are analyzed to simulate the potential benefit in terms of hosting capacity, system losses, and reactive power attained with each method to determine the advanced inverter settings.**

***Index Terms* — advanced inverters, distribution system, hosting capacity, photovoltaics**

I. Introduction

High penetrations of solar PV can impact distribution system operations and power quality, and it is becoming necessary for PV inverters to provide grid support services to mitigate these impacts and increase the cumulative benefits from the distributed generation. The California Public Utility Commission (CPUC) is currently implementing advanced inverters into Rule 21 in a phased process. While these functions [1] are becoming more common, very little work has been done to address the implementation of the function settings and the impact these common functions will have on grid performance.

Methods have been proposed in [2-5] to determine site specific inverter settings, but results show how those settings are highly dependent on the specific scenario analyzed. Previous work also showed that advanced inverter functions can be used for improving feeder response under high penetration scenarios [6-10], which can ultimately improve PV hosting capacity. In [11], a hosting capacity analysis was run on six different voltage constrained distribution feeders. The advanced inverter volt-var function improved the hosting capacity between 43% and 133% with an average increase in hosting capacity of 84%. In [12], a hosting capacity analysis was run on four different distribution systems, with an average increase in hosting capacity of 63% when using volt-var functionality. From these results, there is obviously some potential advantage to applying advanced inverter controls to PV interconnections, but the question of how to determine those settings with minimal side effects remains. There is a significant lack of guidelines and available tools for determining effective advanced inverter functions.

This paper describes methods to determine general (more widely applicable) settings for effective use of advanced inverters using the fixed power factor, volt-var, and volt-watt functions. The end goal is to recommend settings (or methods by which those settings can be determined) for the advanced inverter functions currently being considered as part of the update to Rule 21. These settings would also provide advanced inverter thresholds to enable manufacturers to specify their equipment and suggested defaults. The outline of the paper is to first present the analysis methodology and selected study feeders; second, to develop methods to determine advanced inverter settings that range in complexity; and third, to demonstrate the impacts of the advanced inverter settings on distribution system performance.

II. Analysis Methodology

The impact of the various advanced inverter functions and settings is quantified using EPRI's detailed hosting capacity analysis [13]. The hosting capacity analysis determines the amount of PV that can be accommodated on a distribution feeder without impacts exceeding predefined utility guided thresholds. The analysis approach applied here focuses on the feeder hosting capacity for large-scale PV (utility-class) 500 kW systems interconnecting to the three-phase feeder primary through a step-up transformer. The PV is stochastically deployed and simulated for thousands of potential distributed PV deployments. The analysis investigates the impact from PV during the minimum and maximum load that occurs midday anytime during the year. The PV penetration level is increased until 10 MW of PV has been deployed (20 MW for feeders greater than 15kV). The hosting capacity is finally determined when a stochastically-created PV deployment causes the feeder-wide response to exceed established thresholds.

The original selection of the utility feeders was based on the results of a comprehensive clustering analysis where each feeder from the three California investor-owned electric utilities (PG&E, SDG&E, and SCE) had been characterized and grouped into representative sets [14, 15]. Of the originally selected 22 feeders, 7 were selected for analysis of different advanced inverter functions based on a range of impact from distributed PV [16]. The feeders described in Table I include voltage classes from 4kV to 21kV, but are mostly in the 12kV class. Two of the feeders have line voltage regulators.

A detailed feeder model in OpenDSS was developed for each feeder based on the utility planning model. The OpenDSS distribution software is used so that detailed analysis can be performed similarly across the different utilities even though the original models come from different software platforms.

TABLE I. STUDY FEEDERS AND CHARACTERISTICS.

Feeder ID	Peak Load (MW)	Farthest 3-phase Node (km)	PV Hosting Capacity	Nominal Voltage	Line Regs	Switching Caps
683	3.6	17.9	Low	12 kV	1	1
631	3.4	11.7	Moderate	12 kV	0	1
888	2.2	2.8	Low	4 kV	0	0
2885	9.2	11.9	Low	12 kV	1	6
281	16.7	10.3	High	21 kV	0	6
2921	6.4	15.5	Moderate	12 kV	0	6
420	5.0	4.7	High	12 kV	0	1

To illustrate the impact of advanced inverter settings, a power factor "sweep" was first conducted. This is a brute-force option of running a hosting capacity analysis for the feeder while sweeping the applied power factor setting from unity to 0.9 inductive (absorbing reactive power) power factor. This is a very computationally intensive approach, but it illustrates the benefit/impact from different settings for power factor.

The hosting capacity results shown for Feeder 631 in Fig. 1 illustrate a tradeoff for different power factors. The yellow region illustrates the aggregate PV penetration when adverse impacts begin to occur for some potential PV deployment scenarios depending on individual PV location, while the red region illustrates when adverse impacts occur in all scenarios with that much aggregate PV penetration. By decreasing the power factor to absorb more reactive power, the risk of over-voltage violations decreases, and the over-voltage hosting capacity increases dramatically. On the other hand, a more inductive power factor introduces some under-voltage issues starting around 4MW of PV. Looking at the bottom left of Fig. 1, there is an optimal point of -0.93 power factor that provides the highest hosting capacity for this particular feeder.

There is a clear benefit to utilizing power factor control to increasing hosting capacity; however, the best power factor setting is different for each of the feeders analyzed in Table I. This illustrates the issue utilities are faced with in knowing the appropriate setting for different DER scenarios. Therefore, the contribution of this paper is to provide guidance on determining appropriate advanced inverter settings for different feeders.

For the purposes of this paper, the term hosting capacity refers to when 50% of the analyzed scenarios have a violation. This median hosting capacity is inside the yellow region (bottom left of Fig. 1) and quantifies the "general impact" of an average case. This quantification of hosting capacity is used throughout the rest of the paper to convey the impact of advanced inverters for a typical PV scenario (as compared to best/worst case PV scenario).

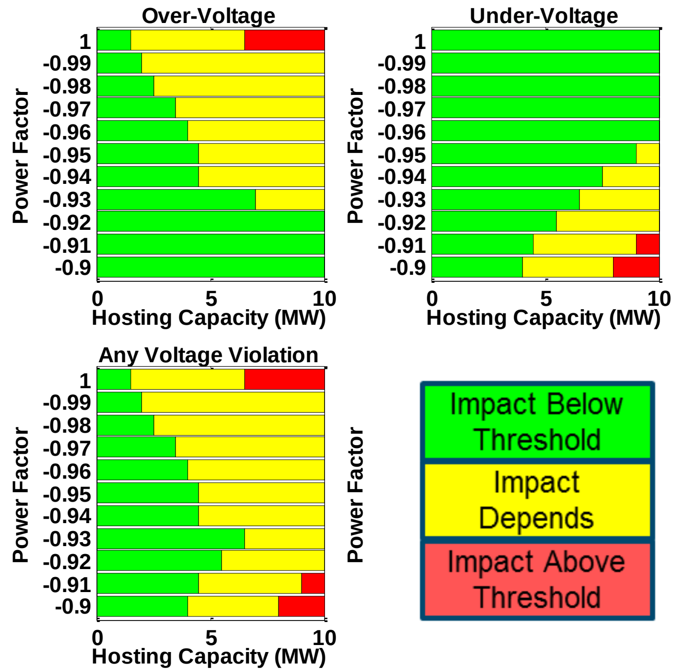

Fig. 1. Hosting capacity analysis for feeder 631 at various inductive power factors.

III. METHODS TO DETERMINE SETTINGS

The methods derived in this analysis are geared around improving the distribution system response from PV. One way to quantify the impact to the distribution system is to observe the benefit the advanced inverter could provide in terms of hosting capacity. In this analysis, hosting capacity is calculated based on system voltage. The objective of each of the advanced inverter methods is to minimize the voltage change occurring from increased levels of PV. The impact on voltage deviation inherently includes the impact on the absolute voltage magnitudes at the primary, secondary, and voltage regulation nodes on each feeder.

The three main advanced inverter functions targeted for this analysis are:

- Power factor – Inductive output based on the real power generated by the PV
- Volt-var – Inductive or capacitive output based on the voltage at the PV inverter
- Volt-watt – Maximum real power output based on the voltage at the PV inverter

Each of these functions can have a direct impact on the operation of the distribution system. Additional advanced inverter functions such as frequency-watt, voltage ride-through, and frequency ride-through have a more direct impact on the bulk power system.

For each of the advanced inverter functions considered, multiple methods are developed in order to determine settings based on the data and tools readily available to the distribution engineer. This has been done to be cognizant of how distribution planning engineers have to cope with various levels of data and resources available to them for examination. The methods are designed in levels to require different input data and simulation resources. Although the focus of this paper is to highlight the procedures to calculate specific settings for a feeder and deployment of PV, the Level 1 (simplest) volt-var and volt-watt methods are defined regardless of the specific location or feeder design/condition (e.g, default setting - see Table II). The lower level methods could be applied with little to no feeder information and spreadsheet tools, while higher levels require more detailed information and software tools to determined exact settings. A detailed description of each method is included in [17].

TABLE II. BASIC DETAILS OF METHODS TO DETERMINE ADVANCE INVERTERS SETTINGS

Level	Complexity	Power Factor	Volt-Var	Volt-Watt
0	None	Unity Power Factor	Disabled, Unity Power Factor Applied	Disabled, Unity Power Factor Applied
1	Low	Based on Feeder X/R Ratio	Default Setting	Default Setting
2	Medium	Based on Feeder Model and PV Location	Based on Feeder Model and PV Location	Not Analyzed
3	High	Based on Feeder Model and PV Location	Based on Feeder Model, PV Location, and Service Transformer	Not Analyzed

A. Inverter Power Factor Settings

The most understood advanced inverter function is fixed power factor. For a single PV system on a feeder, it is straightforward to calculate the power factor necessary to mitigate any voltage deviations caused by the PV real power injection. Using the X/R ratio at the point of common coupling (PCC), the lagging power factor can be directly calculated to absorb enough reactive power to offset any voltage rise from the real power injection [18]. This means that the power factor to negate voltage rise depends on location of the PV, with the most effective solution involving a site-specific setting based upon PCC X/R ratio.

While this method works well for a single inverter, the situation becomes much more complicated for distributed PV with many systems interconnected around the feeder [19]. It is necessary to develop new methods for determining appropriate settings for multi-inverter power factor control. Three methods are proposed that range in complexity, as shown in Table III.

TABLE III. METHODS TO DETERMINE SETTINGS FOR MULTI-INVERTER POWER FACTOR CONTROL.

	Method	Requires Feeder Info	Requires PV Sizes and Locations	Calculation Complexity	Number of Power Factors
L1	Mean X/R Ratio of Feeder	Yes	No	Hand	1 per Feeder
L2	Weighted PCC X/R ratio	Yes	Yes	Spreadsheet	1 or 2 per Feeder
L3	Sensitivity-Based Optimization	Yes	Yes	Optimization	Each PV has unique PF

Level 1 (L1): This method only requires the knowledge of short-circuit impedances of the feeder. Independent of the number, size, or locations of PV systems, the value will always be the same. A simple hand calculation is performed to determine the mean X/R ratio along the feeder, which is then converted to a single power factor number using (1).

$$Power\ Factor \cong \frac{(X/R)_{mean}}{\sqrt{\left((X/R)_{mean}\right)^2+1}} \tag{1}$$

Level 2 (L2): This method requires both the feeder information and the locations and sizes of PV currently installed. A spreadsheet calculation can be used to average the X/R ratios of all PV primary nodes weighted by the PV size in order to determine the weighted average X/R ratio. The primary node X/R ratios are also first adjusted by taking into account the interconnection transformer losses. If the power factor is below 0.9, it is set to 0.9. Optional: For any utility-scale PV system at unity power factor that by itself causes less than 1% voltage rise at its PCC, the power factor is set to unity. This avoids excessive and unnecessary reactive power drawn by the PV system.

Level 3 (L3): The final method for determining settings for multi-inverter power factor control involves a detailed iterative, load-flow-based optimization calculation. The algorithm is developed and presented in [20]. The optimization uses a linear voltage sensitivity calculation based on the voltage changes from real and reactive power injections around the feeder. The objective function of the optimization is to minimize the square of the voltage change at each node, constrained by the power factor being within the range of ±0.9, centered around unity power factor, for each PV [19].

B. Inverter Volt-var Settings

Advanced inverters with volt-var control can mitigate voltage rise, and when set properly, will only activate when necessary. Another advantage of the volt-var control is that it can operate as both inductive and capacitive. In the derivation of these methods, it has been assumed that the PV system inverter is sized 10% larger than the overall rating of the PV panel array.

Level 1: The setting shown in Fig. 2 has been considered by the IEEE P1547 working group and could be applicable in any feeder/DER scenario. The primary objective of a default volt-var setting is to help mitigate unacceptable voltage conditions either caused by the DER or the existing voltage condition of the feeder. The mitigation includes both minimizing overvoltage conditions and, in the case of variable generation such as solar and wind, minimizing the voltage variations.

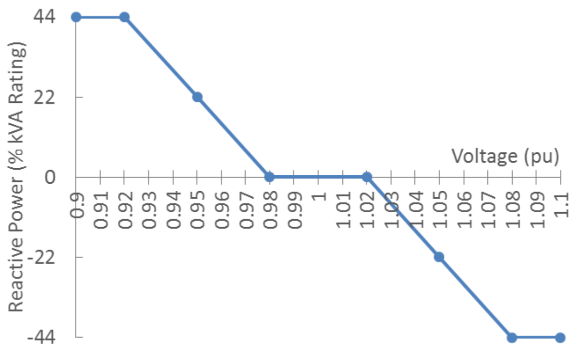

Fig. 2. Level 1 volt-var setting.

Level 2: The Level 2 method is an extension of the Level 1 setting that provides a feeder specific adjustment. There are two options for the Level 2 setting based on the distribution feeder voltage profile. Based on the feeder voltage profile for midday peak and midday minimum load conditions, the distribution planner will determine which Level 2 option to apply.

Level 3: The Level 3 method transforms the Level 2 volt-var settings based on the impedance of the interconnect transformer. Conceptually, this is the same as applying the Level 2 setting (and reactive power requirement) based on the voltage at the medium-voltage side of the interconnection transformer.

C. Inverter Volt-watt Settings

There is only one method/setting defined for volt-watt as shown in Fig. 3. Only one method/setting is defined because reactive power control functions (volt-var or power factor) should be utilized before volt-watt is applied. The method/setting is independent of the feeder/deployment of PV, and setting is designed around not curtailing real power unless the system is experiencing voltage violations.

IV. RESULTS

There is a considerable benefit to the distribution system by using advanced inverters to mitigate adverse voltage impacts, which results in increased hosting capacity. At the same time, there is an impact to the distribution system that allows the increase in hosting capacity. This "Impact" can come in the form of increased losses or the need for local reactive power compensation. The hosting capacity, losses, and reactive power compensation are all compared between each of the control methods and the base line unity power factor scenario as shown in Fig. 4 for feeder 683.

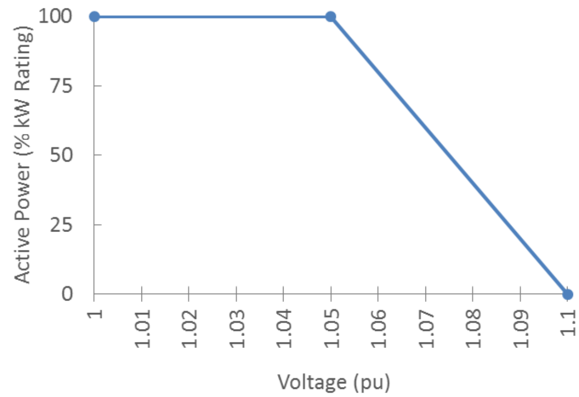

Fig. 3. Level 1 volt-watt setting.

The more complex methods to determine settings for each control can increase hosting capacity, however, if not properly tuned, the setting could present more "Impact" than hosting capacity "Benefit".

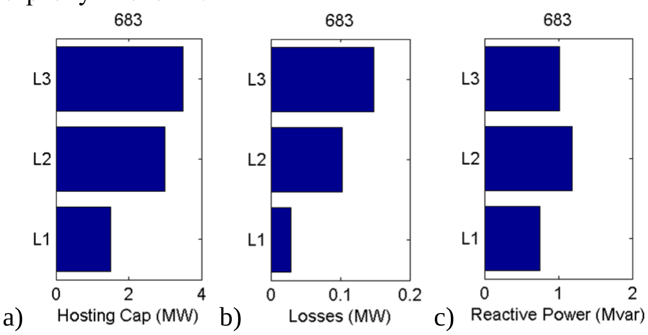

Fig. 4. Power factor increasing a) hosting capacity, b) losses, and c) reactive power.

The ratio of Benefit to Impact is examined to determine how much strain the methods place on the distribution system to attain higher hosting capacities. For this examination, losses are ignored. The ratio compares MW of additional hosting capacity (HC) to the Mvar needed for reactive power (RP) compensation.

The ratio of Benefit to Impact is taken directly even though these are not equitable quantities. On some feeders, the required reactive power compensation may also not be considered an adverse distribution system impact, thus the desired method utilized could be solely chosen based on the potential hosting capacity Benefit.

The ratio of hosting capacity Benefit to reactive power Impact should increase for more complex methods, illustrating higher hosting capacities and the effective use of reactive power. For power factor control, that generally does occur between Level 1 and Level 3 methods as shown in Fig. 5. The hosting capacity for power factor Level 3 only increased for 2 of 7 feeders, thus the Level 3 method more effectively uses reactive power. Level 2 methods do not show a consistent increase in ratio for the seven feeders due to lower hosting capacities, higher reactive compensation needs, or a combination of the two.

The hosting capacity benefit from volt-var Level 1 was low, but in terms of the reactive power required to attain a higher hosting capacity, the Level 1 setting works similarly to more complex methods. Level 2 methods also show a high ratio of Benefit to Impact. The more aggressive Level 3 settings that show a significant improvement in hosting capacity also require more reactive power to do so.

Overall,

- Power factor Level 1 and Level 2 have the least effective use of reactive power
- Level 3 power factor and Level 3 volt-var provided similar increase in hosting capacity and also demand of reactive power, thus their overall Benefit to Impact ratio is comparable
- Volt-var Level 1 had low improvement in hosting capacity yet the control settings have some of the most effective use of reactive power

Due to limited improvement in hosting capacity and no significant improvement in effective use of reactive power, there are not substantial advantages to using the Level 2 methods of volt-var and power factor. If there were no constraint on the reactive power requirement, the preferred methods may include volt-var Level 3, power factor Level 1, and power factor Level 3. When reactive compensation is a limiting factor, the preferred methods may only include volt-var Level 1 or power factor Level 3. Ultimately, the computational requirements to determine the settings for power factor Level 3 may outweigh the value of the results. Therefore, the last method, which happens to be the least complex is volt-var Level 1.

Alternatively, when reactive power is not a limiting factor, power factor Level 1 may appear desirable due to the potential improvement to hosting capacity along with simple calculations for settings. However, another important factor that should be considered is how well the Level 1 settings can be determined. To examine this, a brute force sweep of power factor setting was analyzed on each feeder.

The brute force analysis, illustrated in Fig. 6, verified that the Level 1 method did in-fact provide a setting that was close to the most optimal for each feeder (Level 1 settings are highlighted in Red). However, the brute force method also identified that if the setting were not chosen properly, the Benefit to Impact ratio could quickly shift from positive to negative such as on Feeder 683. This is caused by the sudden decrease in hosting capacity and/or excessive reactive power demand. Overall, based on the seven analyzed feeders, a positive impact is shown as long as the single feeder-wide power factor setting remains equal to or above 0.96.

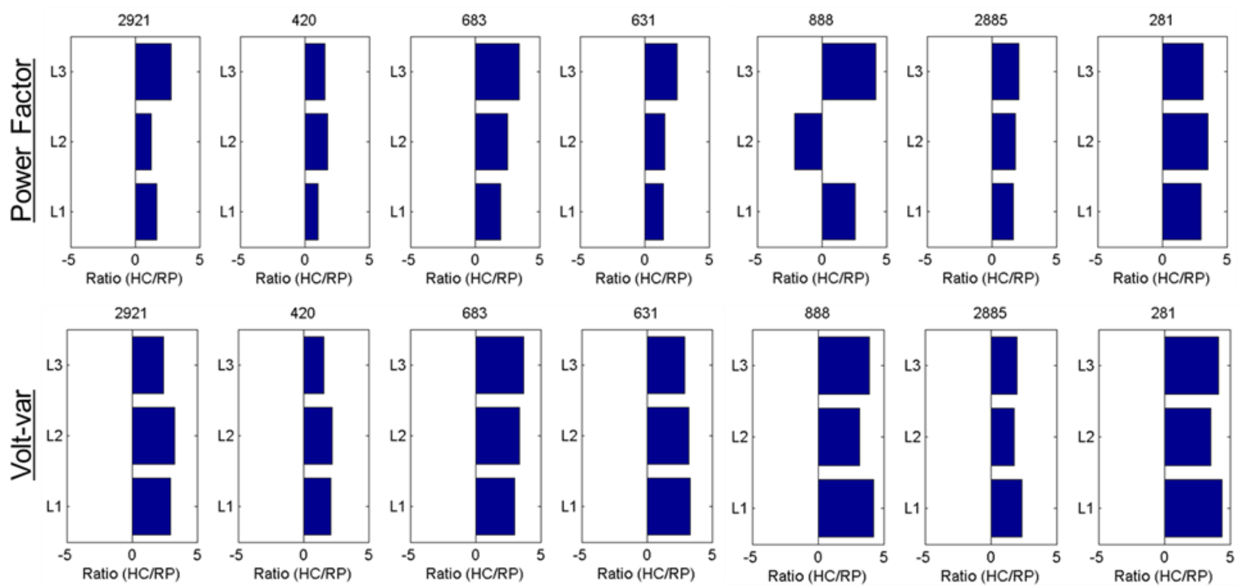

Fig. 5. Ratio of hosting capacity to reactive power for each study feeder and each method to determine the settings.

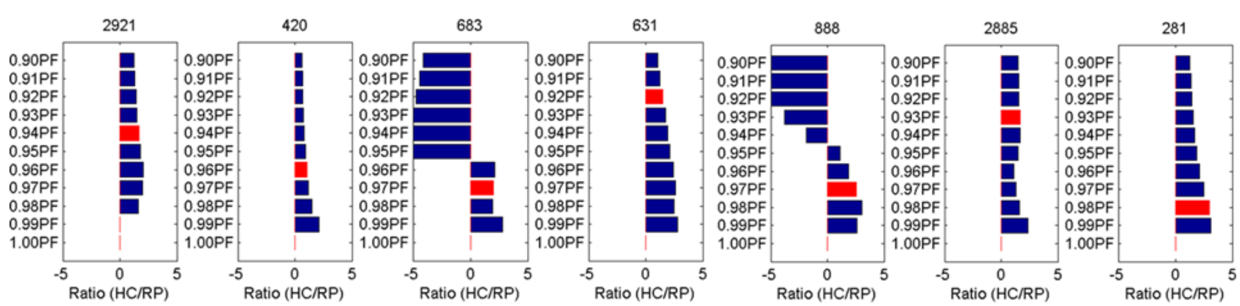

Fig. 6. Ratio of benefit to impact for power factor brute force analysis. The Level 1 power factor settings are highlighted in red.

V. CONCLUSIONS

Advanced inverters have functionality that can allow better integration of distributed energy resources such as PV to the distribution system. At the distribution system, these functions include power factor, volt-var, and volt-watt. This is not an all-inclusive list of functions, but includes those that are at the top of the mind for most inverter manufacturers and distribution engineers.

This paper summarizes the analysis approach (methods) in which appropriate settings for each of the advanced inverter control functions can be derived [17]. Ideally there would be one global setting that works in all situations for each control function; however, as determined in this research, the control settings are strongly linked to the specific feeder in which the control will be applied. For each advanced inverter function, several feeder-specific methods to determine the control settings were developed to be applicable using the data/tools available to utilities. The various methods span the availability of limited data/tools to abundant data/tools with detailed feeder models.

The distribution feeders hosting capacity was shown to improve with the use of advanced inverters using the settings derived with the various methods. Focusing on the Benefit to Impact ratio, some control functions did perform better than others, and the more complex methods did generally allow better accommodation of PV. At the same time, the least complex method (volt-var Level 1) had one of the most effective uses of reactive power. Volt-watt did not show significant benefit/impact, however could be used in conjunction with power factor or volt-var control after reactive power options are exhausted.

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Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

The National Renewable Energy Laboratory’s portion of this work was supported by the U.S. Department of Energy under Contract No. DOE-EE0002061.