Improving Distribution Network PV Hosting Capacity via Smart Inverter Reactive Power Support

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***Abstract* — Many utilities today have a large number of interconnection requests for new PV installations on their distribution networks. Interconnections should be approved in a timely manner but without compromising network reliability. It is thus important to know a network's PV hosting capacity, which defines the upper bound of PV sizes that pose no risk to the network. This paper investigates how implementing reactive power control on the PV inverter impacts the PV hosting capacity of a distribution network. A local Volt-Var droop control is used and simulations are performed in OpenDSS and Matlab. Multiple feeders are tested and it is found that the control greatly improves the overall hosting capacity of the feeder as well as the locational hosting capacity of most voltage constrained buses.**

***Index Terms* — photovoltaic systems, reactive power control, voltage control.**

I. Introduction

Increased adoption of photovoltaic (PV) generation has begun to impact the reliability of distribution networks. In particular, utilities are beginning to see PV contribute to steady-state and transient voltage violations, and the reduced effectiveness of protection devices [1-3]. These issues limit the amount of PV that utilities will allow on their networks. Utilities would like to avoid these time-consuming studies due to the sheer volume of new interconnection requests and FERC has provided some guidelines for when these studies are necessary or when a proposed interconnection may be "fast-tracked" [4]. However, these guidelines are overly simplistic and may lead to systems being installed that should have been studied in more detail or systems being studied that could have been fast-tracked. In general terms, the utilities are interested in knowing what is referred to in recent literature as the "PV hosting capacity" of their networks [5-7]. There are different approaches to representing a network's PV hosting capacity, but all essentially try to determine how much PV a network can install before seeing its first operational violation.

This paper focuses on how transient and steady-state voltage violations limit a distribution network's capacity to host large three-phase PV installations. Voltage limits are often the first violation caused by PV. These violations can also be the least expensive to mitigate. Whereas network equipment thermal violations and protection changes may require the installation of new equipment or costly engineering [3], some voltage violations may be avoided by using the spare reactive power control capabilities of the PV grid-tie inverter. Much research has shown that PV inverters may be used to effectively regulate the voltage at their point of common connection (PCC) [8, 9]. It stands to reason that if a network's PV hosting capacity is limited by voltage violations, then a larger PV system may be installed if it employs voltage regulating reactive power support. This paper studies the use of PV inverters for voltage support and the impact this control has on the distribution network hosting capacity.

This paper is organized as follows. Section II presents the methodology used in the analysis of network PV hosting capacity and inverter reactive power control. In Section III, several test feeders are simulated using this methodology. Simulations are performed in OpenDSS using a Matlab toolbox interface called GridPV [10, 11]. Section IV demonstrates the impact of inverter sizing on the effectiveness of reactive power control to improve hosting capacity. Section V draws conclusions and provides future research directions.

II. Defining Hosting Capacity and PV Control

The research in this paper continues the work in [12, 13] and therefore shares the same methodology.

A. Definition of Hosting Capacity

This research studies the interconnection of a large, three-phase PV plant to the distribution network's medium-voltage network. The network's "PV hosting capacity" is therefore defined as the maximum PV system size that does not violate the network operating standards when interconnected to any valid bus. This means that the voltage of all network buses must remain within the ANSI Range A limits of $0.95 \leq V_{pu} \leq 1.05$ in steady-state [14] and the network currents must remain within the line and device rated limits during steady-state.

B. Control of PV Reactive Power

The PV inverter is controlled in the so-called "watt-priority" control where real power output the PV inverter, P_{inv}, is maximized. This leaves the maximum amount of reactive power available to the inverter, Q_{inv}^{max}, as a time-dependent quantity of the remaining capacity of the inverter's rating, S_{inv}, as follows:

$$Q_{inv}^{max}(t) = \sqrt{S_{inv}^2 - P_{inv}^2(t)} \quad (1)$$

The most widely studied method of using this spare reactive power for voltage regulation is to apply a Volt-Var control curve to the PV system, such as the one in Figure 1. Volt-Var control will output a fraction of the available Vars based on the voltage measured at the PV system's PCC. A deadband near the desired voltage ensures the control does not oscillate and only acts to improve significant voltage deviations. This manner of control is simple, inherently stable, and already gaining traction in the industry [15]. The specific curve selected to control the inverters in this research is shown in Figure 1 and is a typical, conservative choice of control curve.

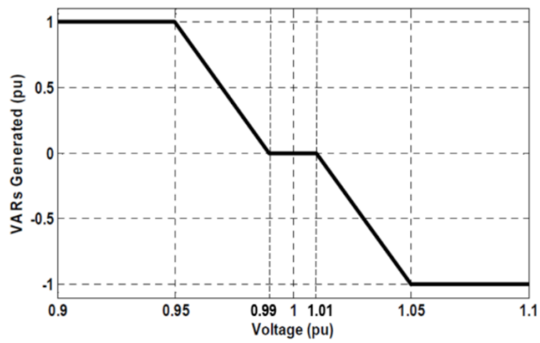

Figure 1. Volt-Var droop control curve used for PV system inverters in this research.

C. Inverter Rating and Insolation

As shown in (1), in order for the PVs to have the capability of providing any reactive power support, there must be spare capacity in the inverter. One way of ensuring spare inverter capacity is to over-rate the inverter's kVA capacity relative to the PV system connecting to the grid. Future grid codes may require some level of reactive power support that would incentivize new installations to oversize the inverter. However, typical large PV interconnections rate the grid-tie inverter either at the same rating of the PV panels or even less. When studying the impacts of PV, activating smart inverter features and over-rating the inverter may be one of the least expensive mitigation strategies for removing over-voltages and increasing a feeder's hosting capacity. Therefore, for this research it is assumed that percent inverter kVA overrating is equivalent to a predetermined margin of capacity in the inverter relative to the real power output of the PV system. This over-rating is assumed to be 120% in this research, a value used in similar research [16, 17]. There is a more detailed discussion of how the overrating of the inverter impacts hosting capacity in Section IV.

III. PV VAR CONTROL IMPACT ON HOSTING CAPACITY

Simulations are carried out on multiple test networks using the methodology described in Section II. Each network represents a single real distribution feeder that is three-phase and unbalanced. A detailed analysis for one of the feeders is presented below, followed by a summary of the key findings for five more feeders. The simulations use the open-source distribution network power flow solver OpenDSS, developed by EPRI, in conjunction with the Matlab toolbox GridPV [10], developed by Sandia National Laboratories and Georgia Tech to interface Matlab to OpenDSS.

A. Impact of PV Inverter Volt/Var Control on Feeder PV Hosting Capacity Profile

The following analysis is for a 12.47kV distribution feeder with peak load of 1.71MVA peak load called Feeder 1. Its PV hosting capacity is limited by voltage constraint violations, as depicted by the yellow region in Figure 2. This figure depicts the percentage of buses in the feeder that will allow a particular size PV interconnection before various violations occur. The green region where no buses have violations up to a certain PV size is considered the feeder's hosting capacity (HC). The blue region is where no violations occur based on the locational hosting capacity (LHC). In Figure 2 there is no inverter reactive power control considered.

The simulation is run again with the inverter assumed to have a 20% margin of kVA capacity over the real power output of the PV system and using the Volt-Var control of Figure 1. The results of this case are shown in Figure 3. Clearly, the voltage regulating control has reduced the yellow voltage violation region. The feeder HC is also increased by 50% from 600kVA

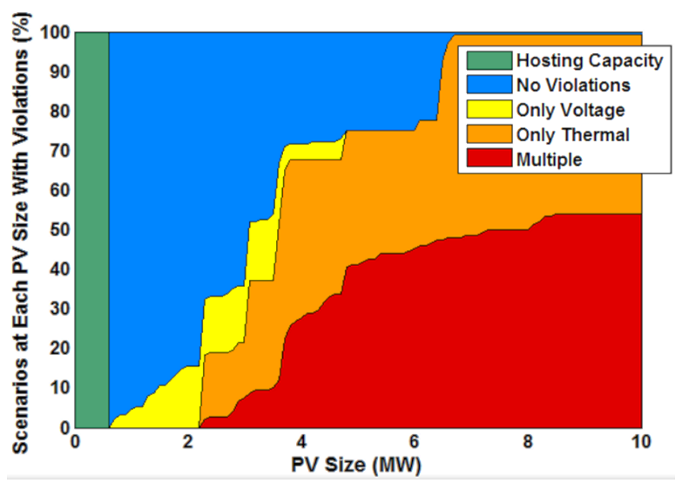

Figure 2. Base case (no inverter control) hosting capacity profile for Feeder 1.

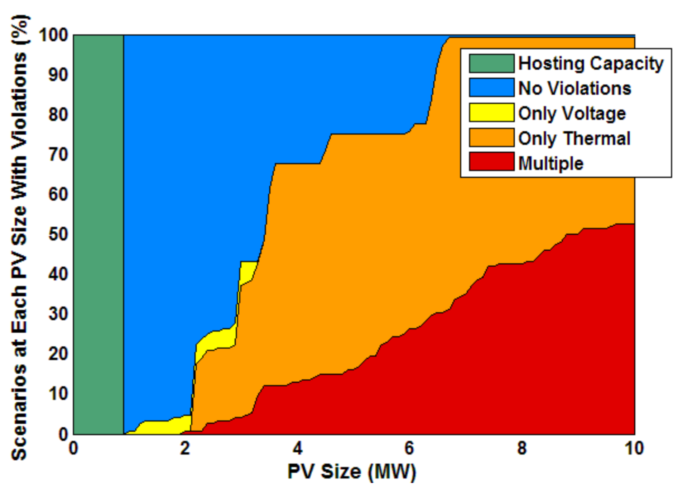

Figure 3. Feeder 1 hosting capacity profile with Volt-Var control of PV inverter.

to 900kVA and the LHC is also expanded to more regions on the feeder.

The violations can be represented geographically by impact type on the feeder one-line diagram, as in Figure 4, which represents the base case with no inverter controls. The marker colors indicate the size of PV that causes a violation, and the marker shape indicates the violation type.

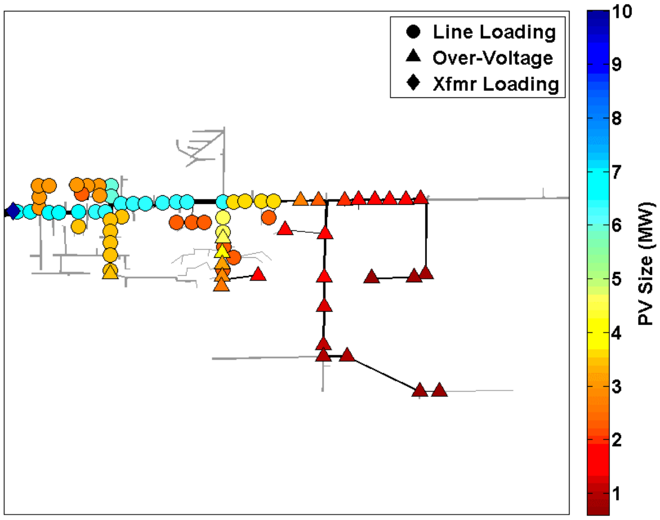

Figure 4. Feeder 1 base case locational hosting capacity.

Comparing to the Volt-Var controlled case in Figure 5, there is a decrease in number of voltage violated buses replaced with thermal violations. For voltage constrained buses, the Volt-Var control improves the HC until a thermal constraint is hit. However, if Volt-Var control is implemented on buses that are thermal constrained they can host slightly less PV since the Volt-Var control on the over-rated inverter increases the current output of the PV system from the base case. Also, many PCCs have robust voltages and gain little benefit from the control. If Volt-Var control is implemented over all PCCs, the LHC only improves by an average of 14.4%. For this reason, Volt-Var

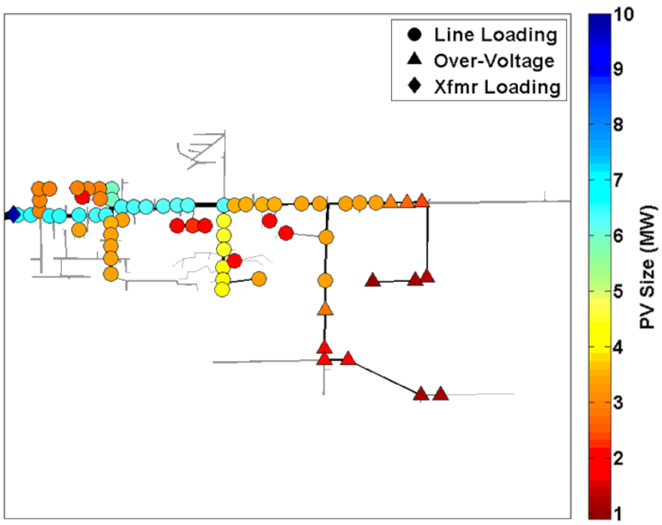

Figure 5. Feeder 1 locational hosting capacity with Volt-Var control on the PV inverter.

control should only be implemented at PCCs that are voltage-constrained in the base case. In Feeder 1, 32% of the PCCs are suitable locations for implementing Volt-Var control.

The average improvement in LHC for voltage-constrained buses is 72.7% for Feeder 1, which represents an increase of over 1MVA per PCC. The maximum improvement in LHC Feeder 1 is 135.7% with the addition of the Volt-Var control. This PCC is capable of hosting a 3.3MVA PV system with a Volt-Var controlled inverter when it was constrained to a 1.4MVA system without the control.

Of course the improvement in LHC is dependant on several factors, including the amount the inverter is over-rated (discussed in Section IV) and the X/R ratio of the feeder. Distribution systems generally have very low X/R ratios, which means the reactive power injection from Volt-Var control has less impact on voltage. The X/R ratio for Feeder 1 is 1.3. This explains why all over-voltages were not removed for this feeder. If the X/R ratio had been higher, or the inverter had more capacity for reactive power injection, all over-voltage violations could be removed by Volt-Var control.

B. Summary of Hosting Capacity Changes Across Multiple Test Feeders

The simulation described above is also performed on five other test feeders. As before, a 20% margin of inverter kVA capacity to PV system kW output is assumed. The summary of the resulting changes in HC due to Volt-Var control are presented in Table 1, with Feeder 1 being the same feeder as in Section II.A. The table summarized the overall feeder hosting capacity increase (HCI). Overall, the local Volt-Var control improves the hosting capacity of the circuits by 84.4%.

Table 1. Summary of hosting capacity increase (HCI) due to Volt-Var control of PV inverters in several feeders.

Feeder #	Voltage (kV)	Peak Load (MVA)	Base HC (kVA)	HCI (kVA)	HCI (%)
1	12.47	1.7	600	300	50
2	12.47	7.1	500	600	120
3	12.47	6.2	1000	600	60
4	12.47	1.17	300	300	100
5	12.47	0.93	600	800	133.3
6	12.47	3.98	1400	600	42.9
Avg.	**12.47**	**3.51**	**733**	**533**	**84.4**

The locational hosting capacity increases (LHCIs) due to inverter reactive power control are summarized in Table 2 for all of the test feeders. A roughly 75% increase in hosting capacity for voltage-constrained locations can be expected on average, or over 1.2MVA per interconnection site. From the last column, one can see that some key locations see well over 100% increases in hosting capacity, with one in particular able to host a 4.5MVA larger system due to the Volt-Var control.

There is a vast difference in comparing the LHC to the HC of the feeder as a whole. Constraining the feeder hosting capacity to the first PCC violation on average limits interconnection sizes to 42.3% of what is viable on the rest of the circuit on average.

Table 2. Summary of locational hosting capacity increase (LHCI) due to Volt-Var control of PV inverters in several feeders.

Feeder #	Avg. Base LHC (kVA)	Avg. LHCI (kVA)	Avg. LHCI (%)	Max LHCI (kVA)	Max LHCI (%)
1	1748	1094	72.7	1900	135.7
2	6306	1780	45.3	3500	212.5
3	2176	571	31.5	2200	115.8
4	1015	1584	160.7	4500	500.0
5	3000	1908	109.4	4600	418.2
6	5007	631	32.3	1000	71.4
Avg.	**3209**	**1261**	**75.3**	**2950**	**242.3**

IV. Impact of PV Inverter Size on Hosting Capacity

For the simulations is Section III, an inverter kVA capacity margin of 20% compared to PV systems real power output is used, however this is an arbitrary value. As discussed in Section II.C, this inverter kVA capacity margin can also be considered as an "oversized" inverter with respect to the PV systems' rated AC output. As some governments begin to require all distributed generation, such as PV, to provide some level of reactive power control, it is not unreasonable to assume that future installations will have oversized inverters to meet these requirements [18]. It is also an effective mitigation strategy and an interesting research question for how much an inverter will have to be over-rated to remove risk of over-voltages due to the specific PV interconnection. This section investigates the sensitivity of the inverter rating to the Volt-Var control's impact on network hosting capacity. The same feeder is tested as in Section III.A under various inverter sizes. The resulting hosting capacity improvements are shown in Figure 6. The blue curve represents the improvement in feeder HC (the green area of Figure 2) and the red curve represents the improvement in average locational hosting capacity (the blue area of Figure 2). Again, the locational hosting capacity improvement only considers voltage constrained buses, since there is no reason to place Volt-Var control on a thermally constrained PV interconnection.

Both curves obviously start at zero improvement with no available inverter capacity and both saturate once all voltage constrained interconnections become thermally constrained. All voltage violations are eventually removed with the Volt-Var control, leaving only thermal limits. This happens approximately when the inverter over-rating equals the inverse of the feeder X/R ratio. Figure 6 indicates the LHC sees larger immediate gains, since it is a reflection of how all voltage constrained buses are benefited by the Volt-Var control and the HC is only reflective of the single worst case interconnection point. It is important to note that HCI and LHCI reflect different quantities and one does not necessarily indicate anything about the other. These patterns are seen in several other tested feeders such that HCI and LHCI may be approximated in terms of inverter overrating, α, as follows:

$$HCI(\alpha) \approx HCI_{base} + \frac{HCI_{max}}{1 + e^{-c\alpha+d}} \quad (2)$$

$$LHCI(\alpha) \approx LHCI_{max}(1 - e^{-\alpha/\tau}) \quad (3)$$

where *c, d,* and τ are fitting constants. The approximations (2) and (3) are useful because they can be used to derive metrics of impact of inverter oversizing. For instance, applying (2) to Feeder 1 and Feeder 2 and solving for the point of diminishing returns, $\partial^2 HCI/\partial\alpha^2 = 0$, result in inverter sizes of 135% and 121%, respectively. Similarly, (3) can be solved for the point at which 95% of the inverter benefits are achieved across the feeder, for example. In this manner, an optimal inverter size with respect to PV panel size can be recommended for different feeder types that will have the greatest impact on improving interconnection hosting capacity.

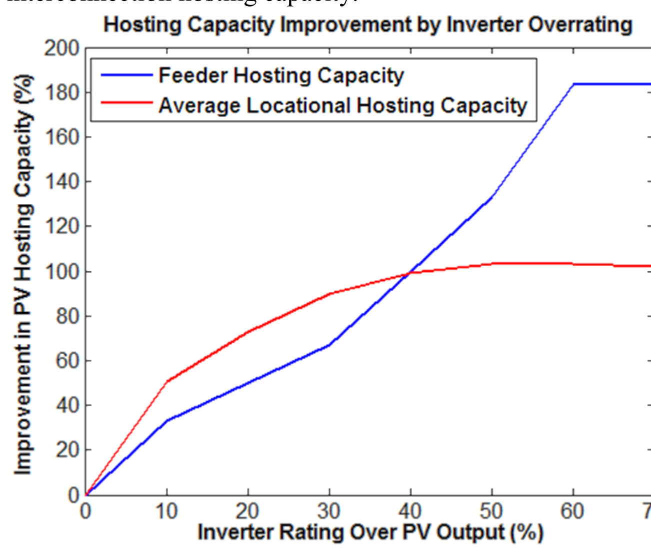

Figure 6. Feeder 1 overall (blue) and locational (red) hosting capacity improvement as a function of PV system inverter oversizing when using Volt-Var control.

V. Conclusions and Future Directions

This paper studies the PV hosting capacity of several real, unbalanced, three-phase distribution feeders both with and without the application of a local voltage regulating reactive power control on the PV grid-tie inverter. A Volt-Var droop control is implemented for PV interconnections that result in voltage violations with the aim of improving feeder hosting capacity. Simulations are performed in OpenDSS via the

GridPV toolbox in Matlab. The results indicate that the overall feeder hosting capacity, which is constrained by the first limiting case per interconnection, improved by an average of 533kVA with the implementation of the Volt-Var control. However, the average voltage-constrained interconnection point allowed for additional PV generation of over 1.2MVA. These results are based on the assumption that the PV grid-tie inverter is oversized by 20%. Studying the sensitivity of hosting capacity to inverter size finds there are large initial gains that graduate saturate.

Further research in this area will study more voltage-constrained feeders and draw correlations based on feeder properties, such as voltage class, loading, and topology. Significantly larger PV systems may be allowed at certain locations with the understanding that smart inverter controls and a guaranteed inverter reactive power capacity are available. The ultimate goal of this research is to develop guidelines for utilities and PV owners that will identify these interconnection scenarios and help reduce the need for costly and time consuming studies.

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