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Quantification of Hosting Capacity Enhancement by Utilization of Smart Inverter Functionalities

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SUMMARY

The adoption of renewable energy resources represents a path in the transition to a low-carbon future mandated in most jurisdictions across the globe. Some jurisdictions have implemented very aggressive renewable portfolio standards that create an imminently challenging scenario, requiring enhanced technical frameworks for distribution system planning and studies. Currently, solar and wind generation is exclusively comprised of inverter-based resources (IBRs), which have profound differences in characteristics and behaviour from conventional rotating-machine-based generator plants. These IBRs are interfaced with the grid through voltage-sourced converters, and their behaviour is entirely dependent on their controls, rather than physical parameters. The modern category of IBRs have oftentimes been termed smart inverters.

Like traditional/legacy inverters, smart inverters convert the direct current output of solar panels or batteries into the alternating current that can be used by consumers. For this reason, they have limitations such as reduced short-circuit contribution capabilities and lack of inertia. However, compared with rotating machine-based generation, smart inverters can provide powerful functionalities and help increase hosting capacity of distribution systems; this means that by leveraging smart inverter functionalities, distribution system operators may be able to accommodate more distributed generation in their system than they would if these functions were not utilized. Smart inverters can provide grid support functions, such as voltage regulation, frequency support, and ride-through capabilities, and they are becoming an integral part of the solution to meet existing technical interconnection requirements based on grid codes and industry standards such as IEEE Std. 1547-2018, UL 1741 SA and SB, IEEE 2800, among others.

All these developments imply a paradigm shift. The distribution system operators of most jurisdictions are now starting to require distributed energy resources (DERs) to enable these functions and indirectly regulate voltage (or even frequency to some extent) on their distribution feeders. This paradigm began shifting since the release of IEEE Std. 1547 2014 addendum and was completely established in the entirely revamped 2018 revision as well as the corresponding UL standards. Quickly, system operators started to revise their technical interconnection requirements to include the enablement of these elements.

KEYWORDS:
smart inverter, hosting capacity, volt/var function, photovoltaic (PV)

1. INTRODUCTION

This paper presents a framework to quantify the value added of enabling smart inverters' grid support functionalities for increasing hosting capacity (HC) of distribution feeders. Generally, one of the most limiting factors for HC is the adverse impact(s) of DERs, especially intermittent renewable resources, on voltage quality of host feeders, both the steady-state voltage raise beyond acceptable ranges (e.g., 1.05 pu) and sudden/rapid changes that cause flicker. The proposed framework includes the quantification of hosting capacity improvement by enabling Volt-VAR and Volt-Watt functions, as well as the sensitivity of implementing default and customized settings for both functions. The Puerto Rico Island grid is used as a case study for the contribution contained in this paper.

Puerto Rico distribution system has over 1,200 feeders with a variety of unique characteristics that could change dynamic performance of the feeders under high penetration of DERs. Examples of the characteristics are voltage levels, short-circuit capacity, minimum/maximum loading, and existing DER amount. In order to select representative distribution feeders for evaluating impact of smart inverter functions on feeder performance, a clustering approach is proposed to categorize feeders into groups of similar attributes. This will help ensure a comprehensive subset of feeders is analyzed with the goal of evaluating effectiveness of proposed settings and functions on the overall distribution systems.

The authors first select a set of representative distribution feeders and conduct studies using various scenarios involving changes in daily/seasonal load profile and solar PV penetration. In multiple stages, PV penetration levels are varied to assess impact on feeder voltages and rapid voltage changes (RVC) with and without the smart inverter functions. Two scenarios of decentralized DERs (roof-top PVs connected to the secondary of existing service transformers) and centralized/nodal DERs connected to given nodes are evaluated to estimate incremental HC increase. A technique is used to extrapolate these results into an entire population of almost 1,500 distribution feeders. Preliminary results suggest that a relatively significant increases in hosting capacity can be achieved if these functions are enabled and their settings are properly adjusted.

The rest of this paper is organized as follows: Section 2 provides a summary of smart inverter functions and their impact on improvement of feeder hosting capacity. Section 3 outlines the overall study approach including the process of selecting representative feeders for the hosting capacity analysis and the study methodology and scenarios. The paper concludes with presenting the summary results of the LUMA feeders case study.

2. IMPACTS OF SMART INVERTER FUCTIONS ON HOSTING CAPACITY

2.1. Hosting Capacity Definition and Analysis

Hosting capacity analysis (HCA) is an analytical tool for quantification of the ability of electrical network for integration of the DERs [3]. Although presently there is no standardized definition for hosting capacity, the industry has adapted a definition suggested by Electric Power Research Institute (EPRI) stated below [1]:

"Hosting Capacity is the amount of DER that can be accommodated in the selected part of a distribution system – either at a node or collectively at feeder level - without adversely impacting power quality or reliability under current configurations and without requiring infrastructure upgrades."

The primary goal of HCA is to assess the capacity and availability of the grid for hosting various DER technologies. The quantification process is based on a series of operational criteria including thermal loading, voltage/power quality and protection coordination to ensure reliability and integrity of the grid. Thus, HCA should be able to evaluate marginal system conditions that are considered unacceptable performance by applying planning criteria under all operating points. To achieve reliable HCA outcome, verified distribution planning models for power flow analysis along with historical/statistical information about load profiles and generation adaptation patterns are required.

2.2. Inverter Voltage-Reactive Power Control Mode Settings

The intermittency of the PV output power causes issues for the operation of the electrical grid. The smart inverters with advanced capabilities for Volt-VAR control (and frequency support) can be deployed to mitigate the adverse impacts of increased PV penetration on the grid voltage (and frequency) levels. Therefore, deployment of smart inverters with Volt/VAR functional capability would support the increase of hosting capacity in the distribution system. This paper studies the impact of enabling the Volt-VAR functionality of the smart inverters on increasing the hosting capacity and examine different Volt-VAR settings to obtain the optimal settings for grid operation.

In Volt-VAR control mode, the Smart Inverter actively controls its reactive power output as a function of voltage, using a Volt-Var piecewise linear characteristic. An example Volt-Var characteristic is shown in Figure 1. The Volt-Var characteristics shall be adjustable within the allowable range as specified by the Electric Power System (EPS) operator.

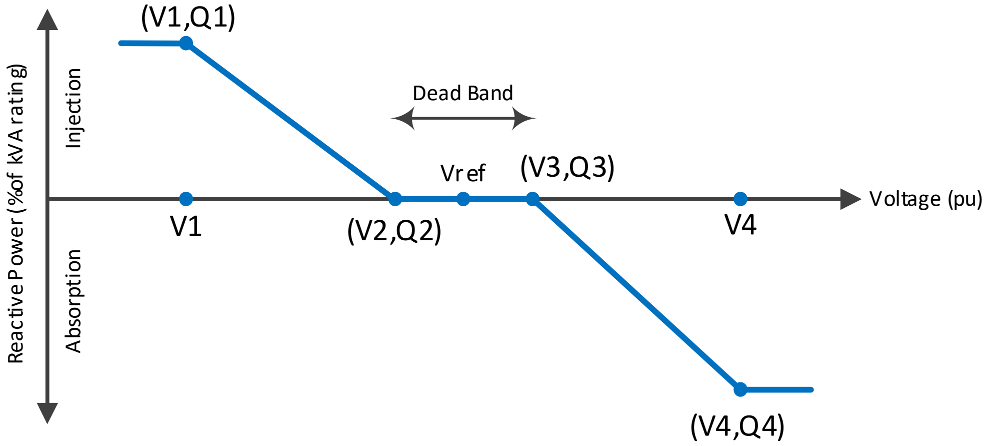

Figure 1. Example Volt-VAR Characteristics

3. STUDY APPROACH

This section summarizes the overall study approach for evaluating the effect of smart inverter Volt-VAR function on increasing the hosting capacity of five representative feeders from LUMA distribution system.

3.1. Clustering Approach for Representative Feeders Selection

The clustering methodology used for this study is based on grouping of feeders with most similar pre-defined attributes. The algorithm for clustering is adopted from the approach described in [2] – where initially k random feeders are assigned to pre-defined number of cluster centers (assuming k clusters are to be formed). In an interactive loop, the clustering algorithm calculates the distance of feeders from every cluster center. Based on the distance, the feeders are re-assigned to cluster with minimum distance (i.e., most similar cluster). Eventually, the clusters are formed in a way that feeders within a cluster are the most similar.

The clustering approach for Puerto Rico distribution system has been determined based on the nature of Puerto Rico distribution system and available information. There are several parameters of the system at substation level which impact the representative characteristic of the feeder and cannot be considered at feeder clustering stage (e.g., high-side voltage level or substation equivalent impedance). Accordingly, the clustering approach is proposed to be performed first at the substation level. Then, within each substation cluster, the feeder clustering will be performed.

Figure 2 summarizes the steps involved in clustering process from defining the strategy (attributes and weights) to categorizing all feeders into different clusters and determining which feeders to study from each cluster for full representation of Puerto Rico distribution system. It should be noted that clustering at substation will be performed by low-side voltage levels, namely, 4.16 kV, 8.3 kV, and 13.2 kV.

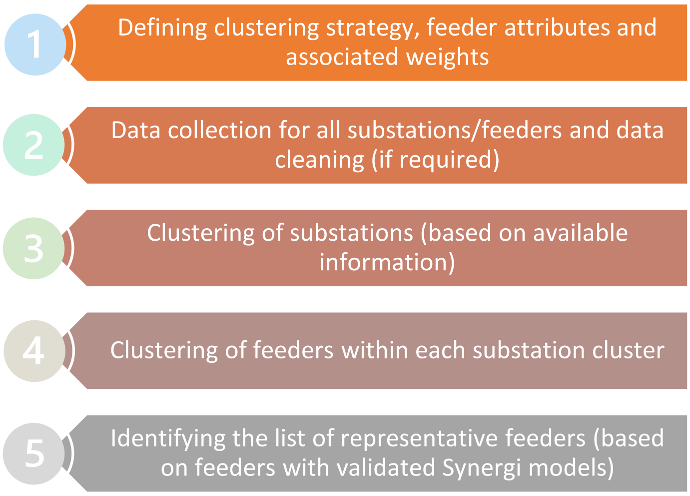

Figure 2. Clustering Approach

Table 1 and Table 2 provide the list of substation and feeder attributes and their corresponding weight for the substation and feeder clustering, accordingly. Three weight factors are used: 5 (highest impact), 3 (medium impact), and 1 (low impact).

It should be noted that a weight of five (5) denotes high impact on clustering results from the perspective of system analysis for smart inverter settings studies. In this case, high-side voltage level and substation equivalent impedance both determine the strength of feeder which overall is a determining factor on how the feeder will respond to penetration of DERs.

A weight of three (3) denotes medium impact, where the impact on system representation is considerable but lower compared to high impact attributes (e.g., loading of the feeder or average length of substation feeders are medium impact attributes). Finally, a weight of low (1) denotes least significant impact compared to two other categories.

Table 1. Substation Clustering Attributes and Weights

No.	Substation Clustering Attributes	Attribute Weight
1	High side Voltage Level (kV)	5
2	Substation Equivalent Impedance (Z%)	5
3	Peak Load to (Substation Thermal) Rating Ratio	3
4	2020 Customer Number (per substation)	1
5	Sum of Feeders Length divided by the Number of Feeders within each Substation	3

Table 2. Feeder Clustering Attributes and Weights

No.	Feeder Clustering Attributes	Attribute Weight
1	Feeder Length	5
2	Designated Feeder Loading	3
3	Daytime Load	3
4	Existing DER amount	1

No.	Feeder Clustering Attributes	Attribute Weight
5	Load Composition (Number of Residential Customers)	5
6	Load Composition (Number of Commercial Customers)	3
7	Load Composition (Number of Industrial Customers)	3

3.2. Simulation Approach and Estimation of Feeder Hosting Capacity Increase

The effect of the Volt-VAR capability of smart inverter functions on the increase of hosting capacity is evaluated by adding PV systems to the feeder with a total size of up to 100% of the maximum loading of the feeder[1]. The evaluation criteria to determine the maximum hosting capacity increase are the voltage level along the feeder and the rapid voltage change (RVC) at the PV locations. The study assumptions and the acceptable ranges for the voltage level and RVC are explained in Section 4.2.

The selection of the PV locations for the studies are based on the following two scenarios:

- **Nodal PV:** In this scenario, PV systems are added to two locations; the middle of the feeder (MOF) and the end of the feeder (EOF) which are selected based on the short circuit values along the feeder.
- **Decentralized PV**: In this scenario, several locations are selected based on the size of service transformers in the section. The PV systems are added to these selected locations (secondary of the service transformer) with the PV size no larger than 150% of the size of the service transformer.

The PV systems are all equipped with the smart inverter Volt-VAR function, and two different Volt-VAR curves (default curve and aggressive curve) are considered to compare their capabilities in maintaining the voltage level and the RVC within the acceptable limits while maximizing the PV size (see Figure 3).

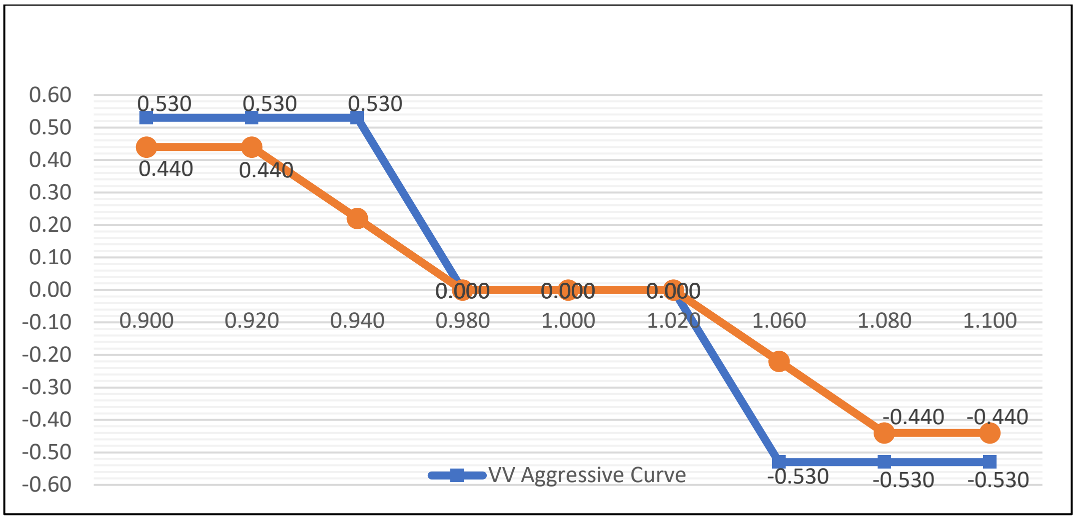

Figure 3. Default and Aggressive Volt-VAR Curves

To evaluate the effect of defined Volt-VAR curves on the amount of additional PV system that can be added to the feeder, we study three cases for both minimum and maximum loading conditions as follows:

I. **Base Case:** PV inverter Volt-VAR curve is not activated.
II. **Default Case:** PV inverter is equipped with Default Volt-VAR (DVV) curve.

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[1] In some cases, up to120% penetration levels were also studied but will not be discussed in details in this paper.

III. **Aggressive Case:** PV inverter is equipped with Aggressive Volt- VAR (AVV) curve.

The maximum PV size are then identified for each of the above cases based on acceptable voltage level along the feeder and RVC of less than 3%. For each feeder, the PV penetration level of nodal and decentralized PV scenarios were compared, and the optimal PV penetration increase were proposed for Cases I, II, and III.

4. STUDY RESULTS

4.1. Representative Feeders

This section provides the summary results of studies for five LUMA distribution feeders to quantify the effect of smart inverter Volt-VAR functions on increasing the hosting capacity for each individual feeder. These five feeders are selected through the clustering process described in Section 3.1, representing the main characteristics of LUMA distribution system:

- 4 kV feeders: F4-01 and F4-02
- 8 kV feeders: F8-01
- 13.2 kV feeders: F13-01 and F13-02

Feeders were selected from different voltage levels to analyze the impact of smart inverter functions under high PV penetration levels.

4.2. Study Assumptions

Below is the set of general assumption considered in the study of the 5 selected feeders.

- IEEE Std. 1547-2018 settings (Category B) were utilized for default VV curve settings.
- The maximum acceptable Rapid Voltage Change (RVC) is 3%.
- For RVC analysis, LTC and voltage regulators tap is kept fixed/locked according to base load condition.
- The acceptable voltage range on secondary network is 95%–105% (114V–126V). Considering ~2V drop for service transformers, the acceptable primary voltage level is assumed to be 97.5%–106.7% (117V–128V).
- LTC bandcenter is 126 V +/- 0.75 (VREF = 126V, BW = 1.5V).
- Capacitor banks status are defined based on loading condition.
- The bandcenter (reference) for all VV curves is assumed to be 120V (1.0pu).
- In distributed approach, the PVs are added to secondary side of large service transformers. For nodal analysis, the PVs are added as a front-of-the-meter.
- The PV Inverter size is assumed to be the same as the PV facility rating ($PV_{MVA} = PV_{MW}$).
- In majority of the cases, the maximum PV penetration considered in the study is 100% of the maximum feeder loading (referred to as the "penetration target").
- The focus of the analyses is the primary voltage of the feeder.

4.3. Study Results

i) PV Penetration Improvement

Table 3 shows the maximum PV penetration level that can be achieved for each of the three inverter Volt-VAR characteristics described in Section 3.2 for the nodal and decentralized PV scenarios. The two feeders F4-02 and F13-02 are robust feeders with higher short circuit ratios and, therefore, they can handle higher amounts of PV penetration without the Volt-VAR curves. As seen in Table 3, for the decentralized approach, these feeders are also capable of hosting the maximum PV penetration that is 100% of their maximum load.

Table 4 summarizes the percentage of PV penetration increase compared to the base case, when no Volt-VAR curve is used. There is a visible increase in the level of hosting capacity by activating the smart inverter Volt-VAR functions. The minimum PV penetration improvement for MOF PV is 14% with either default curve or aggressive curve; for the EOF PV, there is a minimum improvement of 17% with default and 31% with aggressive curve, respectively. For the decentralized case, the minimum PV penetration improvement percentage is 28% for both default and aggressive Volt-VAR curves.

Table 3. PV Penetration Summary Table

	PV Location	MOF			EOF			Distributed		
	VV Curve	No VV	DVV	AVV	No VV	DVV	AVV	No VV	DVV	AVV
PV Penetration (MW)	F4-01 (4kV) (Max load=1.3MW)	1.3	1.3	1.3	0.39	0.575	0.625	0.4	0.55	0.65
	F4-02 (4kV) (Max load=1.5MW)	0.55	0.75	0.9	0.55	0.69	0.79	1.5	1.5	1.5
	F8-01 (8kV) (Max load=2.8MW)	2.3	2.8	2.8	0.725	0.85	0.95	1.8	2.3	2.3
	F13-01 (13kV) (Max load=7.0MW)	1.3	1.8	2.8	0.6	0.95	1.2	3.1	4.3	4.7
	F13-02 (13kV) (Max load=8.5MW)	7.9	9	9	3.4	7.6	8.5	9	9	9

As can be seen in Table 4, the level of hosting capacity improvement with Volt-VAR function is 0% in some case. This means that, for those scenarios, the maximum PV penetration (i.e., 100% of the maximum load) can be achieved even without the Volt-VAR functionality. This happens in cases where the feeder is electrically strong, and the short-circuit level at the PV interconnection point(s) is high.

Table 4. PV Penetration Improvement Summary Table (with respect to No VV Case)

	PV Location	MOF			EOF			Distributed/Decentralized		
	VV Curve	No VV	DVV	AVV	No VV	DVV	AVV	No VV	DVV	AVV
PV Penetration Improvement (%)	F4-01 (4kv)	-	0%	0%	-	47%	60%	-	38%	63%
	F4-02 (4kV)	-	36%	64%	-	25%	44%	-	0%	0%
	F8-01 (8kV)	-	22%	22%	-	17%	31%	-	28%	28%
	F13-01 (13kV)	-	38%	115%	-	58%	100%	-	39%	52%
	F13-02 (13kV)	-	14%	14%	-	124%	150%	-	0%	0%

ii) PV Power and Energy Curtailment

The main negative impact of activating the Volt-VAR function of the PV inverters is the possibility of PV curtailment which occurs in order to maintain the voltage level and RVC within the acceptable range at the PV location. This is especially the case where the PV inverters are not properly oversize to account for reactive power support (note that, in this study, the PV inverter size is assumed to be the same as the PV facility rating). We calculated the PV power curtailment for each of the study cases with Volt-VAR curve and determined the maximum PV power curtailment for each feeder (worst-case scenario using snap-shot analysis[2]). As seen in Table 5, the maximum PV power curtailment is around 8%.

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[2] In the snap-shot analysis, the PV curtailment is obtained assuming that the total PV power generation increases from zero (at t=t0) to maximum or 100% (at t=t1). Then, the power curtailment is calculated as the difference between the actual real power output of the PV systems at these two instances (i.e., $P_{PV\text{-}t1} - P_{PV\text{-}t0}$). Therefore, this will provide the worst-case PV curtailment, which is refereed to as PV “power” curtailment in this study.

Table 5. PV Power Curtailment Summary

Feeder ID	Max PV Power Curtailment with DVV and AVV Curves
F4-01 (4kv)	2.75%
F4-02 (4kV)	7.50%
F8-01 (8kV)	8.10%
F13-01 (13kV)	7.00%
F13-02 (13kV)	4.20%

To consider actual PV and load profiles in the study, time-series analyses were also performed to also obtain PV "energy" curtailment over a period of a year (i.e., 8760 analysis). The study results for one of the representative feeders (Feeder F4-02 with the maximum load of 1.5MW) is presented in this section. The aggressive Volt-VAR curve and two PV locations (MOF and EOF) were used for the timeseries analysis. Two sizes of PV were selected 1.5MW (100% of the maximum load) and 1.8MW that is 120% of the maximum load. The annual energy curtailment based on the 2021 load profile data and typical solar radiation profile for the area under study (for 1.5MW PV) were calculated. As shown in Table 6, the total PV energy curtailment levels are 0% for the MOF interconnection and 0.026% for the EOF interconnection, respectively. These results are 0.002% (EOF interconnection) and 0.3% (MOF interconnection) when a 1.8MW PV system is used for the study, see Table 6.

Table 6. Annual PV Energy Curtailment with AVV (Feeder F4-02)

Location	Annual PV Energy Curtailment 1.5 MW PV (100%)	Annual PV Energy Curtailment 1.8 MW PV (120%)
MOF	0.0%	0.002%
EOF	0.026%	0.3%

5. CONCLUSION

This paper aimed at determining the impact of smart inverter Volt-VAR function on the PV penetration level enhancement. The results of various studies show relatively significant increases in hosting capacity levels that can be achieved if PV inverter Volt-VAR functions are enabled, and their settings are properly adjusted. A scenario planning tool was used to perform various study cases in an automated fashion. It was shown that some feeders can accommodate up to around 30% more DERs with less than 5% annual curtailment under realistic adoption scenarios. These findings are a powerful indication that residential-scale rooftop solar DER can realistically contribute to achieving the territory's renewable portfolio standard goals of reaching 100% renewable energy production by 2050, and with an impressive intermediate milestone of 40% renewable energy production by 2025.

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