

# TAILORING IEEE 1547 RECOMMENDED SMART INVERTER SETTINGS BASED ON MODELED GRID PERFORMANCE

## **National Grid Solar Phase II Program Report**



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## Introduction

Inverter-based distributed energy resources (DERs) such as photovoltaics (PV) are becoming more commonplace in the distribution system. National Grid is experiencing record amounts of solar PV deployment within its service territories, creating an opportunity to operate a cleaner electric grid and help achieve local and national emission reduction goals. Renewable-based DER also brings challenges to the electric transmission and distribution system which include managing the potential adverse impacts on power quality and reliability caused by the intermittent nature of renewable energy. Smart Inverters have been extensively studied to help address these potential challenges and the recent release of the IEEE Std 1547-2018 and its inclusion of reactive power control functionality represent a significant milestone in overcoming such challenges. Electric utilities still face several other challenges that limit the adoption of this new standard; among them is the ability to reliably model and predict the impact that wide adoption of “smart inverters” will have on the electric grid.

In 2017, National Grid (NG) and the Electric Power Research Institute (EPRI) initiated a collaborative multi-year research project to select candidate solar PV sites from actual field deployments, determine the best smart inverter settings for the selected sites based on several critical system conditions, and then monitor the performance of the PV systems with and without the settings implemented to verify expected impacts.<sup>1,2</sup>

In 2019, the research extended further into examining the use of constant reactive power smart inverter functionality for bulk system benefits.<sup>3</sup> Distribution system feeders in areas with low population density may be initially perceived as ideal for solar farms given available open land areas. However, large penetration levels of PV in these areas can be susceptible to transmission system overvoltage conditions. As such, the aim was to investigate the feasibility of utilizing constant reactive power smart inverter advanced grid support functionality to alleviate transmission voltage issues while also avoiding the potential adverse impacts on the distribution system.

In 2020, the study’s key objective extended further to propose a methodology to answer the questions, “How to identify the best

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smart inverter functions to be implemented at a given circuit?” and “What is the best-tailored volt-var smart inverter setting for a set of PV systems in a given feeder based on detailed time-series analysis?” This combined the 2019 time-series study with the methodology used in 2017 to derive best-tailored settings. The primary difference between this study in 2020 and what was conducted in 2017 is the use of time-series feeder performance metrics to develop a methodology that aims to derive the best settings.

## Overview of Smart Inverter Functions

Voltage-related issues are among the most limiting issues regarding the integration of high penetration of DER. In many cases, the use of advanced inverter controls that support the grid can be the least cost solution for mitigating those issues. An example of this is shown in Figure 1. However, applying the wrong settings can increase reactive power flow and negatively impact thermal conductor constraints and feeder power factor. There are benefits from smart inverters and potential adverse side effects that must be considered in all cases.

<sup>1</sup> *Field Performance Assessment of Advanced Grid Support Functions Implemented via Plant Controllers: National Grid Solar Phase II Program Report*. EPRI, Palo Alto, CA: 2020. 3002019417

<sup>2</sup> *Recommended Smart Inverter Settings for Grid Support and Test Plan: Interim Report*. EPRI, Palo Alto, CA: 2018. 3002012594

<sup>3</sup> *Can Smart Inverters on the Distribution Circuit Provide Transmission Voltage Support*. EPRI, Palo Alto, CA: 2020. 3002019418

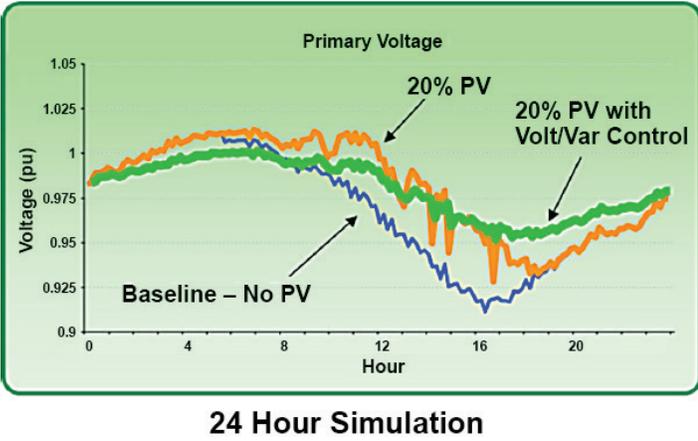


Figure 1. Simulated voltage smoothing with volt-var control

Current tools in development help illustrate the difficulties in determining optimal settings that weight benefits with impacts. The Smart Inverter Settings module within DRIVE (Distribution Resource Integration and Value Estimation)<sup>4</sup> is one example of these tools designed for feeder-wide analysis showing that the best settings differ by location, load level, and objective considered.

Selection of the “best” tailored settings depends upon the primary objectives considered most important. Some objectives, such as reducing reactive power demand and mitigating overvoltages, conflict

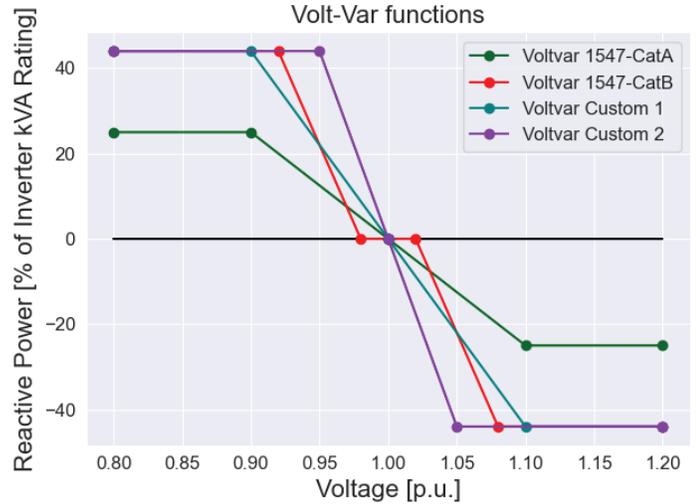


Figure 2. Example of volt-var settings

with one another and, therefore, require thoughtful consideration of several potential competing factors. For instance, Figure 2 shows volt-var functions analyzed with the tool, and Figure 3 illustrates how the best smart inverter function/setting is dependent on location and objective considered for the same feeder. These graphs show the total number of buses (y-axis) for which the smart inverter functions (x-axis) are considered the best settings. Figure 3a is the result of maximizing hosting capacity, while Figure 3b is the result of maximizing hosting capacity and minimizing reactive power consumption.

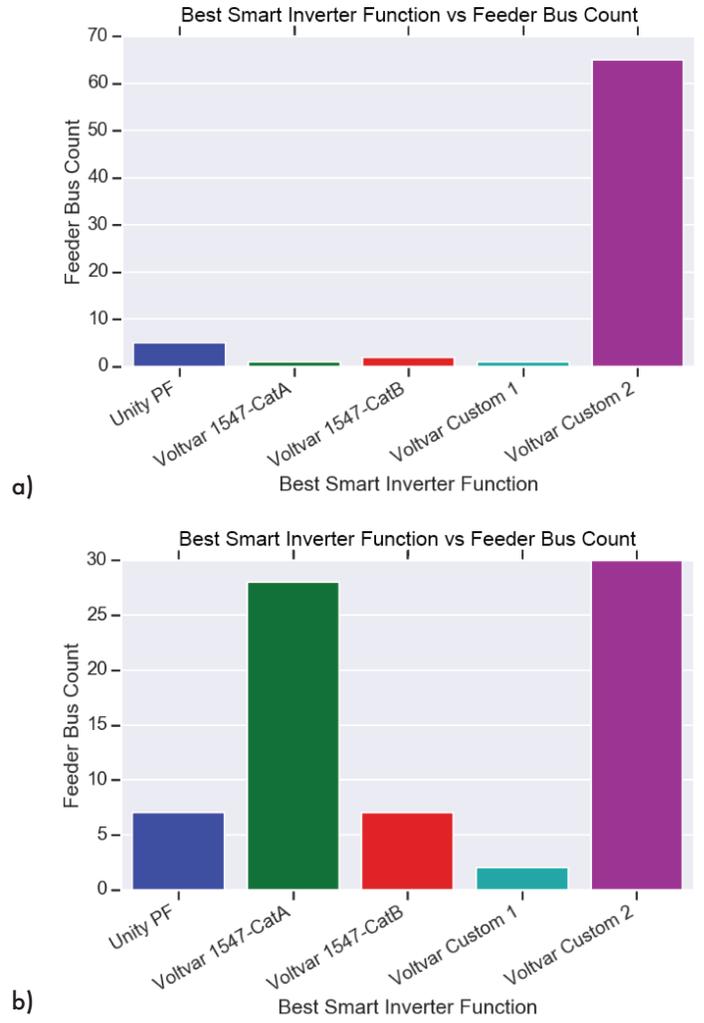


Figure 3. Example of variation of best smart inverter settings. a) Maximize hosting capacity and b) Maximize hosting capacity and minimize DER reactive power consumption<sup>5</sup>

<sup>4</sup> <https://www.epri.com/DRIVE>

<sup>5</sup> DER Autonomous Function and Settings Assessment (DAFSA) – DRIVE Module (Software). EPRI, Palo Alto, CA: 2020. 3002020325



Note that the best functions are dependent on the objective, such as Voltvar 1547-CatA, is the best smart inverter function for more buses in the second case than the first one. It is important to note in this specific case that the custom curves are more often the best function than the IEEE 1547 standard curves. Another interesting observation is that the best setting for some feeder locations is the unity power factor for both purposes; those locations usually are close to the feeder head where the short-circuit impedance is low. This example illustrates how the selection of the best smart inverter function depends on the location and objective. However, it also depends on the feeder characteristics, metrics considered, existing generation condition, and loading condition, among others.

### Objectives and Scope

IEEE Std 1547-2018 defines default volt-var Category A and B settings to aid in distribution feeder steady-state voltage performance. To achieve a more optimal benefit from the volt-var capability, it is necessary to perform modeling of various volt-var settings to assess the overall grid impacts. Therefore, advanced methods and analytics are being established within this project to evaluate multiple volt-var curves and ultimately select tailored settings for the specific feeder conditions and feeder performance metrics (FPM). These FPM can be assessed by measuring a set of eight categories:

- Feeder active power (FAP)
- Feeder reactive power (FRP)
- Feeder power factor (FPF)
- Feeder violations (FV)
- Feeder voltage control elements (FCE)
- Feeder monitored voltages (FMV)
- Point of common coupling (PCC) monitored voltages (PMV)
- PV output powers (PVO)

To truly determine the best inverter settings to improve feeder performance, a detailed analysis representative of the field conditions is required. This involves developing a time-series power flow analysis with detailed grid models and a wide range of inverter settings. Needless to say, countless simulation time and resources will be required to conduct such analysis to evaluate feeder performance through the FPM categories. A thorough yet efficient

analysis can be performed as often as necessary when distribution system state changes must be developed within the utility’s distribution system vendor tool. This report describes the methodology and tool developed and provided to National Grid for that assessment.

### The Proposed Solution

The proposed methodology aims, by evaluating the impact of the different inverter settings on the eight FPM categories, to answer the question “What is the best, tailored volt-var smart inverter setting for a set of PV inverters and feeder conditions based on detailed time-series power flow analysis?” Table 1 provides a definition of each FPM category. Within each FPM category are multiple quantifiable metrics considered for evaluation. Feeder performance will be gauged based on the increase or decrease of each individual metric.

Table 1. Feeder performance metrics

FPM Category	Quantifiable Metrics
Feeder active power (FAP)	Consumption at feeder head, demand, and losses
Feeder reactive power (FRP)	Consumption at feeder head, demand, and losses
Feeder power factor (FPF)	Power factor at the substation bus
Feeder violations (FV)	Voltage magnitude and thermal congestion outside of limits, including length of violation
Feeder voltage control elements (FCE)	Regulator operations, capacitor operations
Feeder monitored voltages (FMV) and PCC monitored voltages (PMV)	Voltage magnitude at user’s selected nodes and PCC buses
PV output powers (PVO)	PV active and reactive power at output terminals

The metrics are time-dependent; therefore, as mentioned before, the methodology requires quasi-static time-series (QSTS) power flow simulations to fully assess the volt-var smart inverter settings’ effectiveness and benefits. The results based on each simulated volt-var curve are obtained, and the best volt-var curve is found.

### Analysis

EPRI has automated the analysis in Python to control NG’s distribution planning software tool and drive yearly QSTS simulations with an hourly time step. The tool needs external information in addition to the feeder model, such as load profile, PV profile, PV

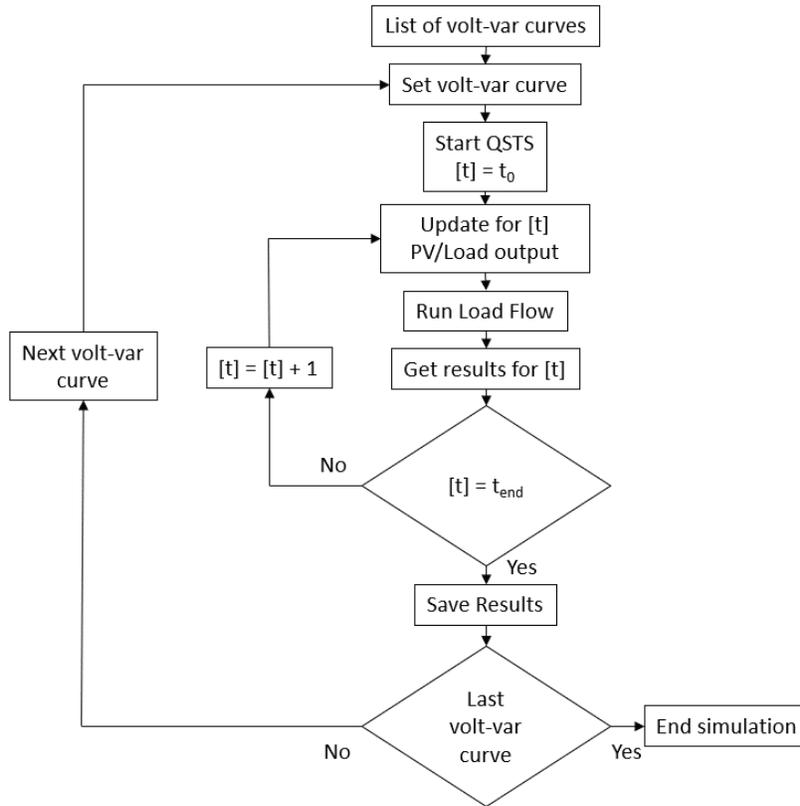


Figure 4. Block diagram of the QSTS simulation process

nameplate information, inverter characteristics, and user-desired monitored nodes. The flowchart shown in Figure 4 represents the conducted analysis process. As a result of this process, yearly FPM (covering all metrics) are produced for each analyzed volt-var curve to derive the best setting.

The following steps describe the analysis:

**List of volt-var curves:** Volt-var settings to be simulated are defined. Figure 5 illustrates an example selection of 173 volt-var curves. The volt-var curves are created by changing the slopes, setpoints, and deadbands.

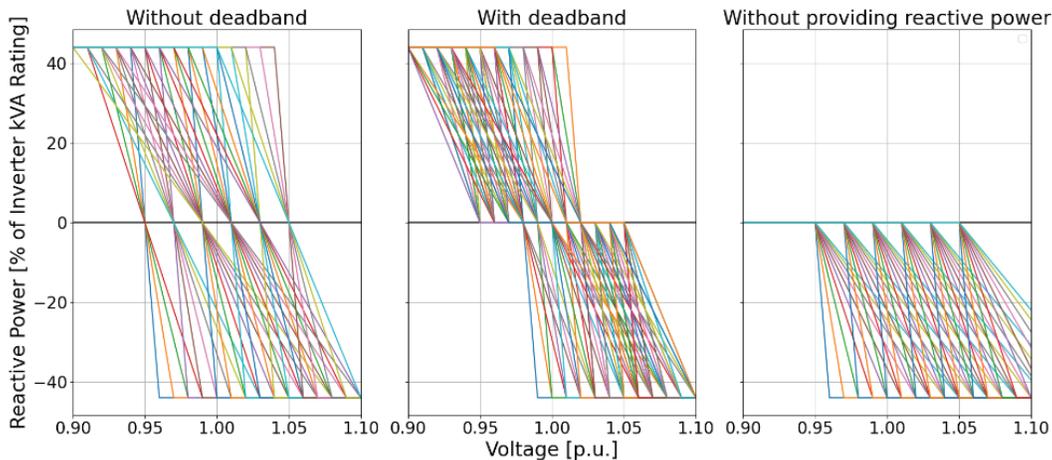


Figure 5. Sample of volt-var settings



**Set volt-var curve:** A single volt-var curve is selected to be applied to each PV system inverter considered in the analysis — all other PV system inverters use existing settings.

**Update for [t] PV/Load output:** At each time step [t] in the QSTS simulation, the analysis updates load consumption and active power output according to the load and PV profiles, respectively.

**Run Load Flow and Get Results for [t]:** After setting the time step [t] condition, the analysis drives NG’s distribution planning software tool to perform the load flow. The reactive power output of the PV inverters is adjusted based on the simulation conditions. Moreover, the inverters can be set to control reactive power at night if the capability is available. Given a converged solution, results are collected for post-processing. The simulation results obtained for each time step are:

1. Power and power factor at the model’s equivalent source
2. System losses, maximum and minimum system voltages
3. Regulators/LTC tap positions – if it exists in the system
4. Capacitor status – if it exists in the system
5. Monitored nodes and PCC voltages
6. Total PVs active power curtailed and reactive power dispatch

**Save Results:** The process ends the analysis for the current volt-var curve and saves the results.

**End Simulation:** The process finishes when it repeats the steps above until no volt-var curve remains.

### Deriving Best Setting

EPRI has automated the process to derive the best setting based on the QSTS analysis results. This process is a relative scoring system in which settings are ranked according to their impact for each FPM rather than according to their absolute performance on that metric. The post-processing is described in the following five steps.

**First step:** The metrics presented in Table 1 are processed for all volt-var curves based on their yearly results obtained from the analysis.

**Second step:** The volt-var curves are ranked for all metrics of each FPM category. Table 2 illustrates how the volt-var curves are ranked for one example metric: number of regulator/LTC operations.

Table 2. Example of the second step of the rank process

Curve	Number of Regulator/LTC Operations	Metric Score or Ranking
VV1	0	1
VV2	10	2
VV3	10	2
VV4	20	4

In this illustration, curve VV1 is ranked first due to the least number of operations and gets a score equal to one. Curves VV2 and VV3 have the same number of regulator/LTC operations after curve VV1; thus, they are ranked second, earning a score equal to two. Curve VV4 has more operations than the other three scenarios; therefore, its score is four. At the end of this step, volt-var curves are ranked for each metric.

**Third step:** The volt-var curves are ranked for each FPM category. The goal of this step is to group the individual metrics into their categories. The category score is the sum of the respective FPM category’s metric ranks; then, the curves are ranked based on each category score. Table 3 illustrates this process, considering the FCE category. Column FCE score has the sum of the rank of the metrics that belong to this category; the number of regulator/LTC operations and the number of capacitors’ operations. Column FCE ranking shows the final position for each curve.

Table 3. Example of the third step of the rank process

Curve	The Ranking of Number of Regulator/LTC Operations	The Ranking of Number of Capacitors’ Operations	FCE Score	FCE Ranking
VV1	1	3	4	2
VV2	2	2	4	2
VV3	2	1	3	1
VV4	4	3	7	4

**Fourth step:** The volt-var curves are ranked based on the FPM categories. The user can define a weight from 0 to 1 to be applied to each category. It provides the user with the ability to give more importance to some categories. The final scores are the sum of the FPM categories’ rankings; then, the curves are ranked based on the final scores. As a result, the curve ranked first is the best for the feeder under the conditions analyzed. Table 4 illustrates the process of obtaining the best curve considering FCE, PVO, and FV categories with weight equal to one and the others with weight equal to zero. The column Final Score has the sum of the three



category rankings, and the Final Ranking column has the curve order positions, which indicates that the VV3 curve is best.

Table 4. Example of the final step of the rank process

Curve	FCE Ranking	PVO Ranking	FV Ranking	Final Score	Final Ranking
VV1	2	1	3	6	2
VV2	2	2	2	6	2
VV3	1	2	1	4	1
VV4	4	4	3	11	4

**Fifth step:** The planning engineer is provided the first few best-ranked curves to allow further engineering judgment.

As can be seen, this process is based upon a scoring system that benefits function/setting combinations that are consistently ranking across the FPM categories, eliminating settings that are low-ranked in some FPM categories while high-ranked in others. It is important to note that the more volt-var curves analyzed, the more competitive the process, and the more likely the best volt-var curve is selected. On the other hand, more simulation time is needed to conduct the analysis.

One of the main objectives of this research has been accomplished, which was to create an automated process with a methodology that could be applied by NG engineers. The next section presents the application of the methodology in two case studies.

### Example of Implementation

The NG feeder (F1) considered in this case study has its single-line diagram with its PV systems shown in Figure 6. This feeder has a primary voltage of 13.8 kV and serves a peak load of 11.4 MW. The voltages along the system are regulated utilizing an LTC installed at the substation, three fixed capacitor banks, and three separate sets of voltage regulators. Each set consists of three single-phase voltage regulators with the same setting. The adjacent feeders are modeled as loads at the feeder head bus to capture the LTC operation.

The feeder has four PV systems, where three are customer-owned sites, and one is owned by NG. Table 2 presents the PV system active power ratings; all PV inverters possess a unity kW-to-kVA ratio and have reactive power ratings equal to 44% of the inverter kVA rating.

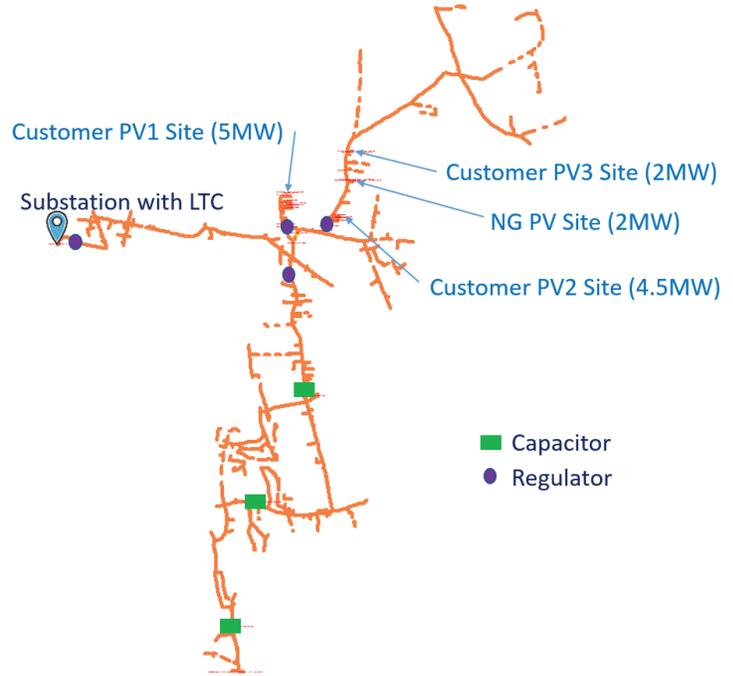


Figure 6. Feeder diagram and PV systems

Table 5. PV active power ratings

Owner	Inverter MW Rating
National Grid	2
Customer 1	5
Customer 2	4.5
Customer 3	2

### Feeder Profiles

All PV systems are assumed to follow the same per-unit PV generation profile as the National Grid PV site, as shown in Figure 7. The load profile utilized that best describes the current load consumption is also shown in Figure 7.

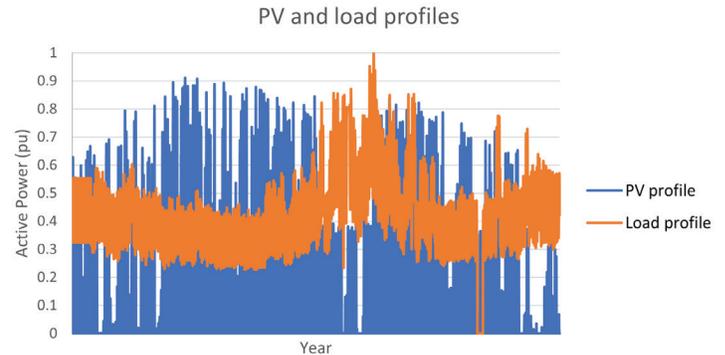


Figure 7. PV and Load Profiles



## Case Studies

The first case study considers that only the NG PV site can operate with the selected volt-var curve. In contrast, the second case study assumes that NG and customer sites can utilize the selected volt-var inverter curve. Both case studies evaluate the same set of volt-var curves (as shown in Figure 5). For these case studies, all FPM category weights are equal to unity.

### Case Study 1 – NG PV Site’s Inverter Considered

Figure 8 shows the best four volt-var curves for Case Study 1 when only the NG inverter is equipped with the analyzed smart inverter settings, and Table 6 shows the characteristics of those curves. As shown in Figure 8 and Table 6, the three first best volt-var curves possess similar characteristics — they have the same setpoint except for Curve ID 25. However, this curve has a similar reactive power absorption compared with the Curve ID 72 and 142 for voltages greater than 1.01 per-unit, as illustrated in the figure. This indicates the selection captures similar, best volt-var curves for the analyzed conditions, essentially providing the best curve characteristics.

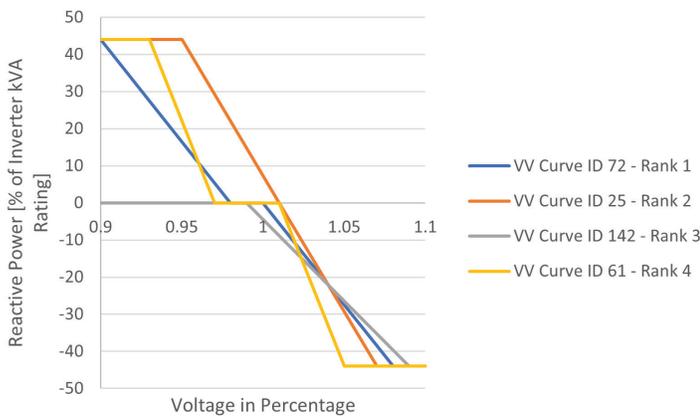


Figure 8. Best volt-var curves for Case 1

Table 6. Best volt-var curve characteristics for Case 1

Curve ID	Final Ranking	Setpoint in pu	Slope	Deadband in pu	Provide Reactive Power
72	1	0.99	5.5	0.02	Yes
25	2	1.01	7.35	0	Yes
142	3	0.99	4.4	–	No
61	4	0.99	11	0.04	Yes
<b>IEEE1547 Cat-B</b>	16	1.00	7.35	0.04	Yes

Table 7 shows the scores of each FPM category and the final rank for the volt-var curves. The planning engineer might use this table to make a final selection based on engineering judgment. For example, the best volt-var curve (ID 72) presents better results than the other three functions for two categories, FRP and FCE, while the second curve (ID 25) has better outcomes for three categories, FAP, FCE, and FV. Therefore, in this case, the planning engineer might define the best volt-var curve as ID 25 instead of ID 72 if FAP, FCE, and FV are more critical than FAP and FCE. The process also provides the engineer with the metric’s results for all scenarios — allowing the engineer to examine more closely the best curve results.

This table also shows the results for one of the IEEE Std 1547-2018 volt-var curves. As can be seen, this curve is ranked 16<sup>th</sup> place — having most of its categories scoring less than the two first, best volt-var curves — illustrating that the standard function is not necessarily the best one. However, it is ranked in 16<sup>th</sup> of 149 positions, indicating that it numbers among the better functions. Note that from the 173 curves simulated, only 149 curves produced results deemed satisfactory for the analysis. The reason is that the distribution planning software did not converge for enough hours of the yearly simulation for the remaining 24 curves. Various solutions could be applied to improve convergence but are out of scope for this project.

Table 7. Best volt-var curves for Case 1

Curve ID	FAP	FRP	FPF	FCE	FV	FMV	PMV	PVO	Final Score	Rank
72	3	4	4	45	20	1	1	49	127	1
25	2	15	44	4	1	1	1	86	154	2
142	16	38	12	22	31	1	1	46	167	3
61	10	31	19	5	18	1	1	88	173	4
<b>IEEE1547 Cat-B</b>	40	27	34	54	17	1	1	85	259	16



## Case Study 2 – All PV Sites’ Inverters Considered

The best volt-var functions and their characteristics are shown in Figure 9 and Table 8 for Case 2 when all connected inverters are equipped with the analyzed smart inverter settings. This case study illustrates that different feeder conditions require unique volt-var curves. Again, Table 8 indicates that the methodology selects similar curve characteristics to be the best ones — curves having the same setpoint and similar slope.

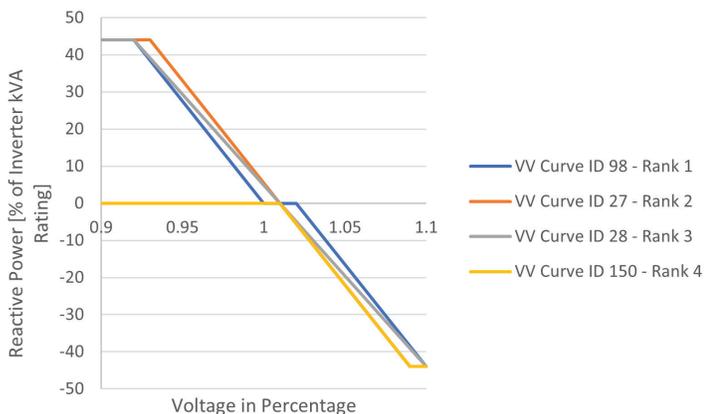


Figure 9. Best volt-var curves for Case 2

Table 8. Best volt-var curve characteristics for Case 2

Curve ID	Final Ranking	Setpoint in pu	Slope	Deadband in pu	Provide Reactive Power
98	1	1.01	5.5	0.02	Yes
27	2	1.01	5.5	0	Yes
28	3	1.01	4.88	0	Yes
150	4	1.01	5.5	-	No
IEEE1547 Cat-B	8	1.00	7.35	0.04	Yes

Table 9 shows the scores of each FPM category and the final rank for the volt-var curves. The IEEE Std 1547-2018 category B curve is again not the best curve but is ranked very well. It is ranked 8<sup>th</sup> of 126 analyzed curves. Note that more curves could not be solved in this case study by the distribution planning software tool — indicating that, the greater numbers of inverters with volt-var, the more challenging it is for the power flow solution to converge.

## Conclusion

Inverter voltage regulation support functions such as voltage reactive power (volt-var) can potentially impact a range of feeder performance metrics due to high PV penetration levels in the distribution grid. A volt-var function’s effectiveness and benefits are drastically dependent on its settings or curve—some curves might positively or negatively impact the distribution grid. To improve integration of PV, avoid adverse impacts, and provide minimum guidance to planner engineers, IEEE Std 1547-2018 defines standard curves that might be a good fit for most distribution feeders. However, the planning engineer might want to evaluate whether or not some functions and settings provide more benefits than those available from defaults defined in IEEE Std 1547-2018. In this case, detailed studies need to be conducted considering QSTS simulation to produce meaningful results. However, this modeling and simulation effort presents a major challenge for most utilities—prohibiting the adoption of the standard. Development of a methodology based on the QSTS simulation tool is required to address this challenge and provide consistency in grid analytics utility-wide.

This report describes the developed methodology that automatically analyzes and selects the best volt-var curves based on weighted feeder performance metrics. It has been designed to be utilized by NG within their distribution grid analysis tool as often as necessary, such as when the distribution grid state changes.

Table 9. Best volt-var curves for Case 2

Curve ID	FAP	FRP	FPF	FCE	FV	FMV	PMV	PVO	Final Score	Rank
98	2	39	11	51	25	1	1	31	161	1
27	24	22	30	15	19	1	1	56	168	2
28	33	26	38	8	17	1	1	54	178	3
150	18	50	43	3	32	1	1	35	183	4
IEEE1547 Cat-B	8	28	45	39	1	1	1	76	199	8



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