Novel Methods to Determine Feeder Locational PV Hosting Capacity and PV Impact Signatures

Matthew J. Reno, Kyle Coogan, John Seuss, Robert J. Broderick

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

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Abstract

Often PV hosting capacity analysis is performed for a limited number of distribution feeders. For medium-voltage distribution feeders, previous results generally analyze less than 20 feeders, and then the results are extrapolated out to similar types of feeders. Previous hosting capacity research has often focused on determining a single value for the hosting capacity for the entire feeder, whereas this research expands previous hosting capacity work to investigate all the regions of the feeder that may allow many different hosting capacity values with an idea called locational hosting capacity (LHC) to determine the largest PV size that can be interconnected at different locations (buses) on the study feeders.

This report discusses novel methods for analyzing PV interconnections with advanced simulation methods. The focus is feeder and location-specific impacts of PV that determine the locational PV hosting capacity. Feeder PV impact signature are used to more precisely determine the local maximum hosting capacity of individual areas of the feeder. The feeder signature provides improved interconnection screening with certain zones that show the risk of impact to the distribution feeder from PV interconnections.
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<th>Description</th>
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<tbody>
<tr>
<td>CVR</td>
<td>conservation voltage reduction</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>EPRI</td>
<td>Electric Power Research Institute</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>GMD</td>
<td>Geometric Mean Distance</td>
</tr>
<tr>
<td>LDC</td>
<td>Line Drop Compensation</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatts (AC)</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>OpenDSS</td>
<td>Open Distribution System Simulator™</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>pu</td>
<td>per unit</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control and Data Acquisition</td>
</tr>
<tr>
<td>WECC</td>
<td>Western Electricity Coordinating Council</td>
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1. INTRODUCTION

Large PV installations on the distribution system can have many potential impacts to local customer power quality and reliability. Conventionally, distribution systems have been designed for voltage regulation and protection coordination considering one-way power flowing radially from the substation to the customers. Adding large amounts of distributed generation may cause two-way power flow changing this historic paradigm and possibly impacting other customers on the distribution feeder. Rooftop photovoltaic (PV) generation is one of the most common forms of distributed generation, and the variability and intermittency of solar power increase the challenges to grid operation. Two common concerns of the interconnection of these systems are steady-state over-voltage and line-loading violations [1]. PV can also cause issues with voltage regulation equipment [2, 3], system losses [4], harmonics [5], low voltages [6], voltage flicker [7], and protection [8].

Before interconnections are approved by utilities, they must go through a screening process to determine if the impact risk justifies requiring an interconnection impact study to thoroughly investigate the potential adverse effects of an interconnection [9]. Currently, such impact studies can be time consuming and expensive, a problem that is only worsened by increasing penetration levels. With increasing numbers of these installations, it is becoming increasingly important for utilities to quickly assess and screen for potential interconnection risks of PV systems.

While PV interconnection impact studies typically investigate a specific location and PV size, another approach is to analyze the entire feeder and determine the feeder’s PV hosting capacity. The concept of hosting capacity (HC) [10] is used to study how much PV can be placed on a feeder before negative issues are caused to normal distribution system operation and power quality [1, 11-13]. The results are feeder-specific, but they are generalizable to any PV interconnection location on the feeder. Using this approach, if the total installed PV on the feeder is less than the hosting capacity, regardless of location, there will be no significant impact to the grid operations. EPRI, along with a couple others [14, 15], has performed significant research in the area of feeder hosting capacity for PV [11, 16, 17]. Work has also been done to show how hosting capacity is a factor of the distribution parameters and can be increased with PV inverter reactive power control strategies [18-22]. The PV hosting capacity of a feeder can also be increased using demand management [23] and active distribution systems [24, 25].

Often PV hosting capacity analysis is performed for a limited number of distribution feeders. For medium-voltage distribution feeders, previous results generally analyze less than 20 feeders [1, 17], and then the results are extrapolated out to similar types of feeders. Previous hosting capacity research has often focused on determining a single value for the hosting capacity for the entire feeder, whereas this research expands previous hosting capacity work to investigate all the regions of the feeder that may allow many different hosting capacity values with an idea called locational hosting capacity (LHC) [26, 27] to determine the largest PV size that can be interconnected at different locations (buses) on the study feeders.

This report discusses novel methods for analyzing PV interconnections with advanced simulation methods. The focus is feeder and location-specific impacts of PV that determine the locational PV hosting capacity. Feeder PV impact signature are used to more precisely determine the local
maximum hosting capacity of individual areas of the feeder. The feeder signature provides improved interconnection screening with certain zones that show the risk of impact to the distribution feeder from PV interconnections. These zone maps can be used for interconnection request screening in a more accurate way that accounts for the feeder characteristics and interconnection location specific information. The detailed analysis is performed on 50 different real distribution systems in order to study the variations in PV locational hosting capacity caused by different circuit characteristics.
2. METHODOLOGY

The analysis is performed in OpenDSS, an open-source three-phase distribution system simulation software developed by EPRI [28]. OpenDSS is controlled through the COM interface by MATLAB using the GridPV toolbox [29, 30]. MATLAB is used for creating and iterating through each PV scenario as well as for the analysis of the results. OpenDSS is used to solve the power flow for each case.

This section presents the methodology of analyzing PV interconnections on the distribution system by size and location to detect when power system operations or quality standards are violated due to high penetration PV. The concepts are presented for simulating large numbers of potential PV interconnection locations and sizes in order to determine the PV hosting capacity by increasing the amount of PV until there are issues.

2.1. Looping through Scenarios

To examine the impact of central PV installations on the feeder, an extensive process is used to step through all considered locations, storing data from the power flow solution for each scenario. The set of scenarios include a significant range of system sizes and locations. The focus of the current methodology is on single, large-scale, central PV plants. Initially, fixed power factor PV systems producing only real power are considered as they are most common [31], but future work will consider active voltage control [20, 32, 33]. For each scenario, the worst case is simulated with the PV system outputting rated power at unity power factor. The basic idea is to place PV at a location on the feeder and increase the PV size until issue occurs, as shown in the flowchart in Figure 1.

During the power flow and violations check blocks, analysis is performed to determine any violations or limitations in the distribution system that would not allow the particular interconnection. These blocks actually represent a series of power flows and tests, as discussed in the following sections. Each power flow simulation is performed in full detail for the distribution feeder with hundreds of components, complex voltage regulation controls, and feeder loads allocated on the secondary system at the end of triplex lines. Each bus is considered individually to find the maximum possible PV size before a violation occurs.
2.2. Violations

PV installations can cause many different issues to distribution system power quality. As PV penetration increases, these impacts can begin to violate certain operational standards are requirements. For the analysis, these types of violations are categorized in steady-state issues (voltage and thermal, system protection issues, and time-based issues such as temporary over-voltage.

2.2.1. Steady-State Simulation

Steady-state simulations are used to detect issues that may occur at particular points in time. These snapshot simulations include voltage regulation equipment being allowed to act and reaching steady-state. In this section, first, the methods for detecting voltage and thermal violations are shown. Second, the methodology for selecting instants for steady-state analysis is discussed. Finally, a methodology is presented for handling potential difference in states for voltage regulators and capacitors.

2.2.1.1. Voltage Violations

All voltages in the system are compared to the ANSI C84.1 Range A standard [34]. As shown in Figure 2, all voltages in the simulations are also broken into the two service voltage categories using the 600 V threshold. For the steady-state simulations, the acceptable voltage range is 0.975-1.05 pu on the primary and 0.95-1.05 pu on the secondary. Anything above this range is considered an over-voltage violation, and any voltage below is an under-voltage violation. The ANSI Range A is used for steady-state simulations because the voltage regulation equipment has acted and any violations would likely persist over the ANSI 10-minute voltage average. The voltage analysis is applied per phase for every bus on the feeder. For the standard 3-phase 4-wire feeder, the voltages are measured as line-to-ground or line-to-neutral voltages. For 3-wire feeders without a neutral conductors, the ANSI range is applied to the line-to-line voltages.
ANSI C84.1 Figure Notes:
a) The shaded portions of the ranges do not apply to circuits supplying lighting loads
b) The shaded portion of the range does not apply to 120 V - 600 V systems
c) The difference between minimum service and minimum utilization voltages is intended to allow for voltage drop in the customer’s wiring system. This difference is greater for service at more than 600 volts to allow for additional voltage drop in transformations between service voltage and utilization equipment.

2.2.1.2. Thermal Violations

Thermal violations are defined as conditions when the current flowing in a conductor is greater than its normal ampacity rating. Thermal violations are also applied to transformers based on their normal kVA rating. For each steady-state simulation, the power flow results are compared to the normal thermal rating to flag any violations.

2.2.1.3. Different Times of Year

The best method to analyze for voltage or thermal issues occurring because of PV would be to simulate a year quasi-static time-series (QSTS) analysis with the feeder load data and PV output data [9]. While this would comprehensively demonstrate if, and how long, there could be issues on the feeder, this type of analysis is very computationally intensive. Simulating a single PV scenario could take hours, and the goal is to effectively analyze thousands of potential PV scenarios on the feeder. One method to reduce the data and computational requirements is to focus on a smaller number of critical or salient distribution operating points, such as peak daytime circuit
load, minimum daytime circuit load, maximum PV generation, and maximum instantaneous penetration [35]. Similar to [11], this analysis uses the most extreme cases to bookend the analysis, meaning if no issues occur in the simulated snapshots, then there must not be issues the rest of the year. For these extreme cases, full rated PV output is used as the worst case. Simulations are performed for a range of potential feeder load values that occur during daytime hours of 10am to 2pm in the year [36], bookended by the maximum and minimum load values during these hours when PV output is high. With the detailed simulations, it is known if a particular PV interconnection could potentially cause issues to the operation of the feeder during the year.

2.2.1.4. State of Voltage Regulators and Capacitors

For a steady-state snapshot simulation at any given time period, there are many different states the feeder could be in as far as regulation equipment taps and switching capacitor states. All potential states of the feeder must be simulated to detect for violations. The analysis methodology is described to include voltage regulation equipment, such as substation load tap changers (LTC), line voltage regulators (VREG), and switching capacitors, to consider and test the range of potential states that are within the control limits of the regulators and capacitors.

For stochastic steady-state simulations, the actual system state (regulator tap position and capacitor connection) is unknown and could be in several different but equally likely states. This is due to the fact that all voltage regulation equipment (LTC’s, VREG’s, switching capacitors) have a voltage regulation setpoint and a voltage band around this setpoint, which are set to maintain the voltage within the voltage band. To prevent an excessive number of operations for the physical hardware that contributes to degradation and wear, the bands on the voltage regulation equipment are set to be fairly large. Having a large regulation band also helps prevent the hardware from nuisance changes, which are when the voltage regulation equipment operates only to have to operate again because the initial operation was over-corrective. If several voltage regulators are in series with each other along the feeder, the regulation band provides a buffer so that every time one regulator changes taps, every other regulator in the series does not also have to change taps.

The presence of the voltage regulation bands means that a given power flow can have several solutions, each equally valid depending on the states of the voltage regulation controls. For example, consider the most common voltage regulator, which is a 32-tap transformer that can regulate the voltage ±0.1 pu and has a 2 V bandwidth. Each tap change increases the voltage by 0.0063 pu. The 2 V bandwidth on a 120 V base is equivalent to 0.0167 pu. This results in regularly having three valid power flow solutions, one for having the voltage regulator on each of the three taps in the bandwidth. An example is shown in Figure 3a where taps 1R, N, and 1L are all inside the voltage control band.

The number of possible solutions increases with a series of VREG’s downstream of each other in succession on a long feeder. For example, if the upstream voltage regulator picks the tap near the top of the band, the downstream voltage regulator could have new possible solutions at lower tap positions.
Switching capacitors in voltage control mode also have a deadband, or hysteresis, in order to avoid constant switching. Capacitors are generally set to connect to a grid at a low voltage and disconnect from the grid at a high voltage. In between the on and off voltage thresholds, the capacitor could be in either the connected or disconnected state due to the hysteresis control. This is shown in Figure 4.

For distribution system simulations, generally the state of the capacitor and VREG tap can be found using external information. Historical SCADA data can include the state of the system for each time period, or analysis of SCADA power data can be used to detect switching events. When performing timeseries simulations, the particular tap at each instant is dependent on the previous state, so the tap is known from the historical load profile and the correct VREG control algorithm implemented in simulation. The possibility of several valid solutions on different taps creates an issue for the hosting capacity analysis methodology because the impact of PV to the distribution system is studied using steady-state snapshot simulations. There is no historical information, either SCADA or previous simulation timesteps, to know which tap each voltage regulation device should be on inside the allowed voltage bands. To prevent this uncertainty, we developed a method.
to investigate each scenario with all voltage regulation at both the top of band and the bottom of band separately. Each power flow solution and check for violations includes two independent power flow solutions at each side of the band to represent all valid power flow solutions. For voltage regulators, the tap is forced to the top of band or bottom of band by reducing the bandwidth of the control and changing the VREG setpoint for each top/bottom of band power flow solution. This is illustrated in Figure 3b. If the voltage control capacitors are within their hysteresis band, they are also checked for both the on and off state. The top of band solution represents the high voltage extremes, so the capacitors are connected if they are in the band. For bottom of band solutions, the capacitors in the hysteresis band are set to off. Every PV scenario is solved for both top and bottom of band control points.

The differences in the feeder voltage profile depending on the top or bottom of band can be substantial. An example of the top and bottom of band voltages for feeder ML1 are shown in Figure 5. The substation LTC in ML1 has a set-point of 121.8V (LDC at R=6 V and X=2 V) with a 3.15V band on a 120V-base. Figure 5a shows ML1’s LTC being forced to the top of the regulating band while Figure 5b shows it being forced to the bottom of the band. An example is also shown for J1 in Figure 6. J1’s substation LTC and 3 voltage regulators all have a voltage set-point of 124V and a bandwidth of 2V on a 120V-base. Figure 6a shows the circuit being forced to the top of the regulating band while Figure 6b shows it being forced to the bottom of the band.

![Figure 5. Circuit plots for ML1 contoured by bus voltage (120V-base) with the regulators set to a) the top of their bands and b) the bottom of their bands](image-url)
With multiple possible taps inside the control band, the voltages in the system and hosting capacity of PV can be significantly impacted by which tap is selected in the power flow solutions. As an example of the implications of voltage regulation being at the top or bottom of their bands, Figure 7a demonstrates the locational hosting capacity of Murray Lake if all of the voltage regulation equipment is forced to the top-of-band while Figure 7b shows the locational hosting capacity if all of the voltage regulation equipment is forced to the bottom-of-band. In both simulations the voltage regulation equipment is locked on the specific tap at the top or bottom of band in the basecase and not allowed to change during the analysis. Over-voltage violations are considered for bus voltages outside ANSI Range A and thermal violations are considered at 100% of component rating. For the former, the average hosting capacity is 5.73 MW. For the latter, it is 11.51 MW. This shows a more than 100% increase in average hosting capacity for this feeder. Moreover, the top-of-band scenario has 94% of its buses’ hosting capacities dictated by steady-state overvoltages. Conversely, the bottom-of-band case has 90% of its buses’ hosting capacities determined by line loading. Clearly, there is a profound effect of tap choice in hosting capacity evaluation. Therefore, it is imperative to account for it in such an analysis.
2.2.2. Protection

Another major area of concern is how PV systems will impact the effectiveness of utility protection equipment. It has been shown that PV generation can impact the fault current seen by protection devices (PDs) \[37\]. This can adversely affect the protection zone of a PD as well as the time-dependent coordination between PDs \[38\]. Further studies have looked at the potential disruption caused by fault currents contributed by PV systems \[39-41\].

The scope of protection analysis is limited to steady-state analysis of distribution networks under fault conditions, so any issues that require the dynamic or time-domain simulation of the PV system in the distribution network are not considered. Also not considered are islanding issues and other PV system protection since these are focused on the PV devices. The implementation and methodology are described in more detail in \[42, 43\]. The four possible protection violations arising from steady-state PV fault current injection are: protection under-reach, PD coordination loss, nuisance tripping, and sympathetic tripping.

- **Protection under-reach:** The protection zone of a PD is the distance into the feeder it can “see” a fault because the fault current is greater than the minimum pick-up current of that PD. Both phase and ground currents are considered. Certain placements of PV systems can diminish this zone by partially supplying the fault current rather than the transmission network. A PD will experience “under-reach” when a PV placement causes a bus in its zone to no longer trip the PD while faulted. An under-reach violation occurs when a fault that caused a PD to trip in the base case is no longer picked up by any PD. If this occurs, an investment is required to re-engineer the protection zone or place more PDs, else risk damaging utility and customer equipment \[37\]. A graphical example of a PD failing experiencing decreased fault current due to a PV on the network is shown in Figure 8(a).

- **Loss of coordination:** Similarly, a PV system placed upstream of a PD can increase the fault current seen by the PD. Therefore if a PV system is between two PDs, it may cause the downstream PD to trip before the upstream PD \[38\]. In the case of reclosers with “fuse-saving” fast trip settings, tripping the downstream fuse will result in a longer outage than necessary \[44\]. The converse is also possible with an upstream PD tripping before a downstream PD which results in a greater number of customers losing power unnecessarily. In this research, it is assumed that the PV system fault current will remain constant for the duration of the fault until a PD clears it. This is not an unreasonable assumption since the fast transient of the PV system only lasts a few cycles \[37\] while the fastest a time-characteristic curve (TCC) that determines when a substation breaker will operate is several times slower than this transient. Using this assumption, the trip time of each PD is calculated using each PD’s unique phase and ground TCCs. This is done for each potential fault type and location under each PV interconnection considered, and a “coordination violation” is declared if an upstream PD trips for a fault downstream of a PD downstream of it. Only under this scenario will a larger number of customers be without power than in the base case with no PV. Fuse-saving failures are not considered in this research. A hypothetical example of an upstream PD picking up before a downstream PD due to their respective TCCs is provided in Figure 8(b).

- **Nuisance tripping:** There is a concern that since most distribution PDs do not have directional sensing, reverse current from PV systems during a fault may be large enough to trip a PD’s minimum pick-up. This issue occurs when the fault current of a PV causes a PD to trip in error.
due to reverse current flow. This can happen in two ways. Under normal operation, a PV can simply be so large that its rated current can pick up the PD under light loading conditions. Under a fault, a nuisance tripping violation occurs only when the PD tripping on reverse current trips faster than the PD designed to clear the fault and the fault must not be located downstream of the PD tripping in error. A graphical depiction of nuisance tripping is shown in Figure 9(b).

- **Sympathetic tripping**: A similar case to nuisance tripping is due to a fault on a neighboring circuit that has additional fault current supplied by PV systems and trips a PD on their own feeder. To test this issue, a short line is placed at the substation and faulted to simulate a close fault on a nearby feeder resulting in reverse current from the PV. A violation occurs when any PD in the network picks up on its minimum trip setting for a particular PV size. A graphical depiction of sympathetic tripping is shown in Figure 9(a).

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**Figure 8.** (a) Example of PV causing under-reach in breaker (b) Example of increased current seen by breaker causing coordination loss.

**Figure 9.** (a) Example of PV causing sympathetic tripping by back-feeding PDs to supply a nearby fault (b) Example of PV causing nuisance tripping by feeding a fault within its own network.
Each of the tests is checked under the four fault types shown in Figure 10, where the network phases are depicted as bold black lines, ground as a dashed line, and the faulted connections in red. For each fault type, $f$, a 0.0001Ω resistance is placed between the appropriate phases and ground as depicted in Figure 10. Only medium-voltage (MV) buses are considered for fault locations since the fuses at the secondary transformer are not modeled and are presumed to trip for any fault on the secondary network since PV are not being tested on the secondary network and should therefore not interfere. The 1LG fault is tested at all MV buses, the 2LG and LL fault types are placed at buses with at least two-phases, and 3LG faults are placed at three-phase buses.

![Figure 10. Fault types considered for analysis](image)

(a) Single-line-to-ground (1LG) (b) Three-line-to-ground (3LG) (c) Line-to-Line (LL) (d) Two-line-to-ground (2LG)

If any issue of protection under-reach, coordination loss, nuisance tripping, or sympathetic tripping are detected during a fault, this is classified as a protection violation that limits the amount of PV that can interconnected on the distribution system.

For the protection analysis, the PV is modelled as unbalanced 3-phase wye-connected constant-power current-limited source that approximates an inverter. The PV injected fault current is limited to 2pu of the rated output. The PV system is connected with a wye-wye interconnection step-up transformer. For more details on modelling the PV system under fault conditions in OpenDSS, see [42].

Each PV interconnection is tested at all MV three-phase buses. This results in a significant number of fault analysis simulations, approximately calculated as: (the number of potential PV interconnection locations) * (the number of potential fault locations) * (the number of possible fault types) * (the number of possible PV sizes). In order to reduce the computational burden, the fault current for each phase of each PD is approximated by fitting a third-order polynomial to each PV location and fault type and location [42]. The number of test buses is also reduced by using a reduced order network model [45].

Due to limitations in the distribution models received from some utilities, the protection analysis is only included in this report for feeders QS1, QL1, QL2, QN1, QB1, and QW1. It should also be noted that this research currently only considers the substation breaker and network reclosers as PDs.

### 2.2.3. Temporary Over-Voltage

In order to accurately characterize extreme voltages that may occur on the feeder due to PV, it is necessary to simulate ramps in PV power to detect any potential temporary over-voltage (TOV) conditions that may occur before the regulators react after their delay period. Solar irradiance can have very large variability and significant quick ramp rates. While, the size of the geographical
footprint of the PV plant can smooth the expected variability compared to a point irradiance sensor [46], the power output can still ramp many MW’s in a minute under extreme cases. For the distribution system, the short-term variability is significant because it can occur faster than the voltage regulation equipment can react. Most voltage regulation equipment has a delay of 30 to 90 seconds, so the 1-minute ramp ramps provide a reasonable comparison for the magnitude that PV can change before the distribution system has reacted. To analyze the impact of PV variability on the distribution system, the worst case scenarios with the highest ramp rates are studied. Looking at the top 0.1% of 1-minute ramps, a 32 MW plant can ramp more than 10.56 MW, and a 24.5 MW plant can ramp 8.58 MW [47]. Similarly, a 80 MW plant can ramp more than 14.4 MW in a minute [47]. From this, it is assumed that a large plant can ramp approximately 10 MW in the time delay of the distribution system.

For smaller plants, the per-unit ramp rates are higher, but the ramp in MW per minute is smaller. Small systems generally have 99.9% of their ramp rates under 50% of capacity. The worst ramp can be higher almost up to 70%, but almost all systems have a 1-minute ramp rate of 0.5 at 99.9%. This can be seen for a 5 MW system in [47], a 4.5 MW system in [47], 13.2 MW system in [48], and three systems greater than 10 MW in [49].

To simulate the impact of extreme PV power output ramps rates, a simple formula is used to calculate the ramp size. For smaller systems under 20 MW, a 50% ramp magnitude is studied. For larger systems greater than 20 MW, a 10 MW ramp magnitude is used in simulation. Both up ramps and down ramps are simulated for system impact. For the up ramp, the appropriate ramp magnitude is subtracted from the total PV size and OpenDSS is used to solve for the state of the voltage regulation equipment at the smaller PV output. The voltage regulation equipment is then locked and the PV output is increased to full output. The down ramps are studied using a similar method of locking the voltage regulation equipment at full PV output and decreasing the PV size by the ramp magnitude. This is done for every PV deployment size, location, load level, and feeder state performed for steady-state analysis discussed in Section 2.2.1.

The effect of PV ramping events is demonstrated on the voltage profile after up and down ramps. Feeder ML1 is shown in Figure 11 and J1 is shown in Figure 12. A 2.5 MW PV plant was placed on both feeders, as shown by the star on each plot. Voltage regulation in each case is being forced to the top of their bands.
Figure 11. Circuit plots for Murray Lake at full load contoured by bus voltage (120V-base) with a 2.5MW PV system and voltage regulation at the top of their bands shown for the 4 different solve modes: a) Steady-state b) PV down ramp c) Steady-state before up ramp d) PV up ramp
Figure 12. Circuit plots for J1 at full load contoured by bus voltage (120V-base) with a 2.5MW PV system and voltage regulation at the top of their bands shown for the 4 different solve modes: a) Steady-state b) PV down ramp c) PV steady-state before up ramp d) PV up ramp

Figure 11a and Figure 12a depict the results of a steady-state solve. For this solve mode, the PV is outputting rated power and the voltage regulation equipment is allowed to act freely, so as to settle into a steady-state solution at the top of the regulations bands. Once this steady-state solution is obtained and the pertinent data is recorded, the regulation equipment is locked. The PV system is then set to output half of its rated power (if the PV system’s rated power is above 10MW, then it is set to output its rated power minus 10MW). After solving, we obtain the plots shown in Figure 11b and Figure 12b. The overall voltage profile of each feeder has decreased.

Now, with the PV system still outputting half its rated power, we once again allow the regulation equipment to act freely, obtaining a steady-state solution for the half-PV case. This solution is shown in Figure 11c and Figure 12c. This change allows the voltage profile to return to a state more similar to those shown in Figure 11a and Figure 12a. Lastly, to simulate an up ramp, the regulation equipment is now locked, and the PV system is set to output its rated power. The results of this are shown in Figure 11d and Figure 12d. As expected, this results in the most extreme high voltages in the figures.
While ramping events create more extreme voltages, they are also only temporary. For example, after 45 seconds, Figure 12d will return to Figure 12a as the regulators change taps. The temporary over-voltages (TOV) should not be compared to the ANSI C84.1 Range A standard (voltage must be less than 1.05 pu) that applies to 10-minute average voltage in normal conditions. Since a ramp would be a temporary voltage violation and deviation of around 30 seconds until the voltage regulation equipment operates, the CBEMA or ITIC curve is used [50]. Assuming the temporary over-voltage lasts at least 0.5 second, the limit is 1.1 pu voltage. For under-voltage, a temporary under-voltage is considered anything less than 0.9 pu voltage, since voltage control actions are often around 30 seconds later when voltage regulation equipment will bring the voltage back into ANSI Range A.

![ITI (CBEMA) Curve (Revised 2000)](image)

**Figure 13.** ITIC curve for temporary voltage deviations.

### 2.2.4. Violations in the Basecase

For some feeders at certain load levels, violations exist on the feeder before PV is even added. This could cause the simulations to end immediately and the hosting capacity to be listed as zero PV that can be added to the feeder, due to the pre-existing violation. In some cases, the violation is an under-voltage, and PV actually improves the voltage, alleviating the violation at higher penetration levels. Situations like this should not classify the PV hosting capacity as zero, even though there is a violation. In other words, if the utility has allowed specific voltages or line loading on the feeder (even if it is slightly overloaded or outside standards), PV interconnections should be allowed as long as they improve the state of the feeder.
For each violations analysis, the basecase values are stored for each load level. For example, the voltage at each bus will be compared to the voltage at that bus in the basecase. If the increase in PV system size is alleviating the violation (decreasing a maximum voltage / increasing a minimum voltage), the analysis does not consider this a violation caused by PV, even though the values are outside the standards. The same methodology is applied for the thermal loading of each line and transformer. The simulation proceeds to increase the PV system size until the hosting capacity is reached when values are outside standards and any values being checked for violations are worse than the basecase.

2.3. Overall Methodology

For each PV scenario, a series of simulations is performed to determine if that particular scenario would cause issues on the distribution system. The simulations include a range of load values that occur during daytime hours throughout the year, a range of feeder states as far as regulation equipment taps and switching capacitor states, and simulation of extreme PV output ramps. For the protection analysis a range of fault locations and types are simulated to detect potential issues for any possible fault. The standards and methodology for defining a violation was described previously in Section 2.2.

The flow chart in Figure 14 shows the entire hosting capacity methodology for analyzing each bus location by increasing the PV size until there is a violation. The four power flow solutions are shown for steady state of PV output, a down ramp, and an up ramp in PV output. The loop for trying the possible extreme ends of the power flow solutions inside the band of each voltage regulator device is shown when the VREG’s and capacitors are set to bottom of band and then top of band. This is all inside a loop that first solves under the extreme peak load that occurred during daylight hours, and then again for the minimum daytime load period. Finally, the protection analysis checks all fault locations and types to detect any issues of under-reach, loss of coordination, nuisance tripping, or sympathetic tripping.
Figure 14. Flow chart of solution methodology for hosting capacity for single large PV plants.
3. FEEDER PV HOSTING CAPACITY

3.1. Locational Hosting Capacity

After analyzing the effect of different PV sizes and locations on the distribution system power quality and operations, the results can be compiled to determine when violations occur. The maximum amount of PV that can be interconnected at a location before a violation is called the locational hosting capacity. The maximum possible PV system sizes are plotted on the circuit topology, shown in Figure 15, varying marker color to correspond to relative maximum system size. The shape of the marker demonstrates the type of violation that limited the locational hosting capacity at that bus. For example, the upward-pointing triangles marking over-voltages are at the ends of the feeder. Looking at this figure it is quickly apparent which parts of the feeder can handle more PV and the optimal locations that will have little impact.

![Figure 15. Locational hosting capacities for Ckt5.](image)

3.2. Determining Feeder PV Impact Signatures

In order to improve the interconnection study process, the use of feeder PV impact signatures are proposed to group feeders by allowable PV size as well as by their limiting factors for the interconnection [51]. The feeder signature separates feeders into different impact regions with varying levels of PV interconnection risk, accounting for impact mitigation strategies and associated costs. After performing the analysis of hundreds of thousands of PV scenarios, the results can begin to be classified by how often a given PV size is permissible at different locations around the feeder. The figures below (Figure 17 - Figure 18) classify the violations into regions based on either voltage or thermal violations. The definition for each region is shown in Figure 16. Region A and Region B both contain allowed interconnection locations that have no violations. Region A is the area that would be found using a total feeder hosting capacity approach that would
give one number for the maximum allowed PV anywhere on the feeder. Region A includes the PV sizes below which a system could be interconnected anywhere on the feeder without further investigation. The other regions refer to system sizes that require further consideration before determining the feasibility of a PV system. Region B contains interconnections that are ultimately allowed but must use some locational details such as PCC distance to the substation and/or conductor type before making this assessment. Regions C, D, and E all include interconnections that have at least one violation and therefore cannot be connected given the current state of the feeder without some mitigation. Regions C, D, and E contain interconnections that respectively result in either only voltage violations, only thermal violations, or both voltage and thermal violations.

![Figure 16. Feeder regions legend.](image)

The feeder signatures (Figure 17 – Figure 18) show the differences between the feeders in the defining factors for their areas of risk. The best way to analyze the figures is to look at individual vertical slices in the graph. For example, for the vertical profile of a 5 MW PV interconnection on Ckt7, 11% of the possible interconnection buses are in Region E, 55% are in Region D, and 34% are in Region B. Ckt7 is almost entirely defined by line thermal limits, which makes this 3.5MW threshold a costly barrier to surpass. Ckt5’s hosting capacity, on the other hand, is completely defined by over-voltage violations. The barrier present around 1.6 MW is easily increased to 3.5+ MW by altering LTC setpoints. Feeder ML1, in contrast to the other two, is a combination of only voltage limits and only line thermal limits.

![Figure 17. Feeder signatures for a) Ckt5 and b) Ckt7.](image)
The simulation results presented show how a PV hosting capacity analysis can be used to obtain a feeder impact signature. This feeder signature separates a feeder into different impact regions that present varying amounts of PV interconnection risk. The regions relate to specific zones of the feeder where PV is easily interconnected, possibly requires some impact mitigation strategies, or definitely presents risks that may be cost-prohibitive. This analysis is expanded to a larger set of feeder topologies and PV interconnection types in later sections.

### 3.3. Feeder PV Impact Zones

As seen in the previous section, there is significant advantage to including interconnection locational information into the analysis. For example, the hosting capacity of Ckt5 is 1.6 MW, but the locational hosting capacity of specific points on the feeder is much higher. In Figure 19, the feeder interconnection zone map for a 6 MW interconnection on Ckt5 shows that there are 25% of the buses that are capable of handling such a system. The feeder zone maps also improve interconnection screening through showing the risk associated with the interconnection. At 6 MW, half the buses with interconnection issues are only caused by voltage violations that may be easily fixed by changing voltage regulation equipment settings or adjusting the power factor on the PV inverter.
Figure 19. Feeder interconnection zone map of 3-phase line sections for a 6 MW PV plant on Ckt5.
4. CHARACTERISTICS OF 50 DISTRIBUTION FEEDERS

The PV hosting capacity work presented in the previous sections was developed to analyze the risk associated with different feeder topologies and characteristics. The analysis is performed for a large range of different distribution systems from various utilities throughout the United States [9, 52-56]. In total, 50 different feeders are simulated so that the risks associated with interconnecting PV on different feeder topologies can be determined. This novel and very detailed analysis has never been performed on so many feeders before. Previous work includes hosting capacity analysis of 18 feeders [17], and 28 feeders [57]. The 50 feeders analyzed will provide new insight into the feeder characteristics and locational information that correlates with high penetrations of distributed PV being able to be installed.

Each of the 50 feeders is an actual distribution systems located around the United States. For proprietary information reasons, the locations of each feeder cannot be disclosed, and all names have been removed. The models were provided by approximately 10 different utilities, encompassing everything from the west coast to the east coast. For all except 3 feeders, the utility also provided at least a year of substation SCADA measurements for the feeder. When load data existed, the minimum and maximum peak load that occurred on each feeder during high daytime PV output (10am to 2pm) [36] is used for the analysis. For the two feeders where the load data is unknown (K1 and M1), the average daytime min and max ratio from the other feeders was applied.

There is a wide range of feeder types, including industrial, urban, commercial, rural, and agricultural. Each model includes the full details about substation impedance, voltage regulator settings, and capacitor switching controls. The load allocation method used for each feeder varies depending on the data provided, such as billing kWh data, metered peak demand, etc. In each case, the feeder peak load measurement was used as the load allocation time. Each feeder also includes an approximate model of the secondary system, often using standard transformer impedances by kVA size and 100 feet of 1/0 triplex cable between the transformer and the customer. Due to the number of feeders, some infrequent features are captured, such as 3-wire feeders without neutral wires and feeders with multiple voltage levels due to step-down transformers.

The voltage classes of the feeders range from 4 kV to 34.5 kV. Figure 20 shows the number of feeders at each voltage class. As expected, approximately two-thirds of the feeders are at the 12/12.47 kV voltage class. There is also a range in the incoming transmission system voltage at the substation for each feeder. The high-voltage transmission side ranges from 46 kV to 230 kV.
The majority of the feeders (41 of 50) have no voltage regulators on the feeder itself, but as seen in Figure 21, there can be up to 6 regulators on a feeder. In total, there are 25 voltage regulators in the database of 50 feeders. There are several different types of voltage regulators, including wye-connected phase regulators, gang-operated delta-connected regulators, and open-delta regulators. Two of the feeders also include boosters that increase the downstream voltage using a fixed tap.

Both the fixed and switching capacitors are modeled for each feeder. As seen in Figure 22, the feeders have between 0 to 7 capacitors per feeder. The feeder with 7 capacitors has a total of 9.9 MVAR of capacitance on the feeder. Most of the switching capacitors are voltage-controlled, but there are also time-controlled, temperature-controlled, kVAR-controlled, time-biased voltage-controlled, and seasonally-controlled capacitors.
Figure 22. Histogram of the number of capacitors on each of the 50 feeders.

Figure 23 shows the range in the peak load for each of the feeders. The lowest feeder only has a peak of 0.6 MW, and the highest is 28.5 MW. Of course the feeder peak load is highly correlated with the voltage class of the feeder. For the hosting capacity analysis, the minimum and maximum load measured during the period of 10am to 2pm for the year is used. As a percentage of the peak load, the minimum daytime load ranges from 12% to 75% of peak load. The maximum daytime load ranges from 71% to 100% of peak load depending on the feeder.

The 50 feeders range in length from 1.8 km to 29.4 km. Figure 24 shows the total length of 3-phase and 1&2-phase medium-voltage (MV) conductor vs. the farthest 3-phase bus for each feeder. There is a significant spread in the length and amount of conductor for each feeder. The ratio of 3-phase conductor to non-3-phase conductor also varies significantly between feeders.
Similar to the length of feeder, the number of buses in each feeder model varies significantly from 125 to 6001 buses per feeder. Many of the key characteristics are shown for each of the 50 feeders in Table 1 and Table 2. For the hosting capacity analysis, only 3-phase buses that are at least 20 meters away from the substation and at the voltage class of the feeder are tested. The number of PV test buses for each feeder is shown ranging from 69 to 1275 buses. The ampacity ratings of the 3-phase medium-voltage (MV) conductors is shown for each feeder in the tables. The feeder backbone is defined as the 3-phase MV line with the highest ampacity rating that has at least 500 meters of conductor in the feeder.
<table>
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<th>Name</th>
<th>Voltage (kV)</th>
<th>Feeder Peak (MW)</th>
<th>Daytime Peak (MW)</th>
<th>Daytime Min (MW)</th>
<th>Farthest 3-phase Bus</th>
<th>Total MV</th>
<th>Total MV 1&amp;2 Phase</th>
<th>Backbone</th>
<th>Lowest</th>
<th>VREGs</th>
<th>Boosters</th>
<th>Total Cap kVAR</th>
<th>Fixed Caps</th>
<th>Switch Caps</th>
<th>Total Buses</th>
<th>PV Test Buses</th>
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<td>0.85 (100%)</td>
<td>0.25 (27%)</td>
<td>10.7</td>
<td>23.4</td>
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<td>18.5</td>
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### Table 2. Characteristics of Feeders 26 – 50.

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<th>Name</th>
<th>Voltage (kV)</th>
<th>Feeder Peak (MW)</th>
<th>Daytime Peak (MW)</th>
<th>Daytime Min (MW)</th>
<th>Farthest 3-phase Bus</th>
<th>Total MV 1&amp;2 Phase</th>
<th>Total MV Backbone</th>
<th>Lowest VREGs</th>
<th>Boosters</th>
<th>Total Cap kVAR</th>
<th>Fixed Caps</th>
<th>Switch Caps</th>
<th>Total Buses</th>
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<td>82.6</td>
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5. RESULTS

5.1. Discussion of the Results for Each Feeder

The impact of PV on distribution system operations is highly dependent on the voltage level of the feeder. At higher voltage levels, the same size PV system will inject less current at the feeder voltage. For this reason, the hosting capacity analysis has been split into four different voltage categories. The first category is 4 kV feeders that are only analyzed up to a maximum size of 5 MW of PV. The second category of 12-14 kV feeders are analyzed up to 10 MW. The third category of 16-21 kV feeders are analyzed up to 15 MW. The fourth category of 33-35 kV feeders are analyzed up to 20 MW.

The detailed results for each feeder are included in Section 5.3. As an example, each figure from feeder QS1 on page 56 is shown here and described in more detail.

First, the circuit diagram topology is shown in Figure 25 with the key components marked. The capacitor marker shows if the capacitor is fixed or switching, and the arrow text gives the size of each capacitor. For QS1, the capacitors are seasonally switching, so for the analysis they are fixed into the correct state depending on the time of year. For QS1, the peak load is 9.25 MW, and the maximum and minimum daytime load (10am to 2pm) is 8.92 MW and 1.96 MW respectively.

![Figure 25. Feeder QS1 circuit diagram.](image)

Figure 26 shows the voltage profile for feeder QS1 without PV at the maximum and minimum daytime load period. In Figure 26, all voltage regulation equipment, including capacitors, have
been forced to the top of their band. To conserve space, the bottom of band simulations are always part of the analysis, but the figures are not shown. For QS1, the bottom of band simulation results in similar voltage profiles as those shown in Figure 26, except they are 1.69 V lower on average.

![Max Daytime Load - Top Of Band](image1)
![Min Daytime Load - Top Of Band](image2)

Figure 26. Feeder QS1 voltage profile for the basecase without PV.

The feeder PV impact signature for QS1 is shown in Figure 27 and Figure 28. These types of figures were described in more detail in Section 3. Figure 27 shows the number of scenarios (PV interconnection locations) at each size that create each type of violation. For example, on QS1, 25% of 4 MW PV interconnection locations would cause a transformer to be overloaded, 65% of 4 MW PV interconnections would cause an over-voltage, 73% would cause a line to be overloaded, and 90% of any 4 MW PV interconnections would cause some issue on the feeder. Figure 28 demonstrates the same sort of analysis using regions with over and under-voltage grouped into the yellow region of only voltage issues that could be mitigated easily. The orange region includes overloaded line or transformers that would be much more costly to mitigate.
Figure 27. Feeder QS1 PV impact signature for each violation.

Figure 28. Feeder QS1 PV impact signature with regions.

Figure 29 shows the locational hosting capacities of QS1 marked by the type of violation that is limiting the locational hosting capacity at that bus. For example, the upward-pointing triangles marking over-voltages are generally at the end of the feeder. The color of each marker is the maximum amount of PV that can be interconnected at that location without causing any issues.
The locational hosting capacities shown in Figure 29 can be analyzed and grouped into what caused the violation. Figure 30 shows a histogram of the violation type determining the locational hosting capacities for QS1. This is essentially a chart of the percentage of markers in Figure 29 that are each shape. The diagonal strips also show if locational hosting capacity at that bus was limited during the minimum or maximum peak load time. For example, any bus where the locational hosting capacity is limited by line overloads almost always occurs during the minimum daytime load period because the reverse current due to the PV injection is higher when the feeder load is lower.

Figure 31 presents a histogram of the size of the locational hosting capacities in QS1. This is essentially the percentage of markers in Figure 29 that are each color. The histogram in Figure 31 is also colored to show which violation caused the locational hosting capacity to be that size. For
example, all buses with the small locational hosting capacities around 1 MW were caused by over-voltage violations.

![Histogram of Locational Hosting Capacity by Violation Type](image)

Figure 31. QS1 histogram of the size of the locational hosting capacity throughout the feeder.

These figures are shown in Section 5.3 for each of the 50 feeders.

### 5.2. Overview of Feeder Results

The locational hosting capacity results are summarized in Figure 32 through Figure 35. Note that each figure is grouped by voltage class and that the maximum PV size varies. The color contour shows the percent of PV scenarios at each PV size that cause any violations on the feeder, corresponding to the black line in Figure 27.
Figure 32. Percent of PV scenarios with violations for the 12-14 kV feeders.
Figure 33. Percent of PV scenarios with violations for the 4 kV feeders.

Figure 34. Percent of PV scenarios with violations for the 16-21 kV feeders.

Figure 35. Percent of PV scenarios with violations for the 33-35 kV feeders.

5.3. Results For Each Feeder
4.0 kV, 2.21 MW peak load
Max daytime load = 1.88 MW (85%)
Min daytime load = 0.63 MW (28%)

Bottom of Band bus voltages average 1.92V lower

PV Impact Signature

Locational Hosting Capacity
4.0 kV, 1.84 MW peak load
Max daytime load = 1.62 MW (88%)
Min daytime load = 0.33 MW (18%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 1.89 V lower

PV Impact Signature

Locational Hosting Capacity
12 kV, 4.43 MW peak load
Max daytime load = 4.37 MW (99%)
Min daytime load = 0.72 MW (16%)

Bottom of Band bus voltages average 3.99 V lower

PV Impact Signature

Locational Hosting Capacity
### DA2

**12 kV, 10.35 MW peak load**

- Max daytime load = 8.93 MW (87%)
- Min daytime load = 1.64 MW (16%)

**Voltage Profile: Basecase without PV**

Bottom of Band bus voltages average 4.08 V lower

**PV Impact Signature**

**Locational Hosting Capacity**

**Histogram of Violation Determining Locational Hosting Capacity**

- Over-Voltage
- Under-Voltage
- Line Loading
- Transformer Loading
- Multiple Violations

**Histogram of Locational Hosting Capacity by Violation Type**

- Over-Voltage
- Under-Voltage
- Line Loading
- Transformer Loading
- Multiple Violations
12 kV, 8.08 MW peak load
Max daytime load = 6.14 MW (76%)
Min daytime load = 3.70 MW (46%)

Bottom of Band bus voltages average 3.06 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type
DC2

12 kV, 3.60 MW peak load
Max daytime load = 2.55 MW (71%)
Min daytime load = 0.62 MW (17%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 2.52 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Violation Determining Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type
DE1

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 3.01 V lower

PV Impact Signature

Hosting Capacity
No Violations
Only Voltage
Only Thermal
Multiple

Histogram of Locational Hosting Capacity by Violation Type

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

Over-Voltage
Under-Voltage
Line Loading
Transformer
Multiple
DK1

12 kV, 3.59 MW peak load
Max daytime load = 3.59 MW (100%)
Min daytime load = 0.74 MW (20%)

Bottom of Band bus voltages average 3.97 V lower

PV Impact Signature

Locational Hosting Capacity
DS1

12 kV, 10.20 MW peak load
Max daytime load = 8.13 MW (80%)
Min daytime load = 1.49 MW (15%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 2.21 V lower

PV Impact Signature

Locational Hosting Capacity
12 kV, 3.42 MW peak load
Max daytime load = 3.39 MW (99%)
Min daytime load = 0.42 MW (12%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 3.93 V lower

PV Impact Signature

Locational Hosting Capacity
**Voltage Profile: Basecase without PV**

**Max Daytime Load - Top Of Band**

**Min Daytime Load - Top Of Band**

Bottom of Band bus voltages average 1.99 V lower

**PV Impact Signature**

**Locational Hosting Capacity**

12 kV, 5.16 MW peak load
Max daytime load = 5.07 MW (98%)
Min daytime load = 1.37 MW (26%)

**Histories at Each PV Size With Violations (%)**

- Any Violations
- Over Voltage
- Under Voltage
- Line Loading
- Xfmr Loading

**Hosting Capacity**

- No Violations
- Only Voltage
- Only Thermal
- Multiple

**Histogram of Locational Hosting Capacity by Violation Type**

- Over-Voltage
- Under-Voltage
- Line Loading
- Transformer Loading
- Multiple Violations

**Histogram of Violation Determining Locational Hosting Capacity**

- Peak Daytime Load
- Min Daytime Load
QM1

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 1.81 V lower

PV Impact Signature

Locational Hosting Capacity

Hosting Capacity
No Violations
Only Voltage
Only Thermal
Multiple

Over-Voltage
Under-Voltage
Line Loading
Xfmr Loading
Multiple Violations

Histogram of Locational Hosting Capacity by Violation Type

Line Loading
Over-Voltage
Under-Voltage
Xfmr Loading
Multiple

Percent of Locations (%)

Host Capacity

Peak Daytime Load Min Daytime Load

PV Size (MW)

Histogram of Violation Determining Locational Hosting Capacity

Percent of Locations (%)

Over-Voltage
Under-Voltage
Line Loading
Xfmr Loading
Multiple

Violation Type

Histlon of Locational Hosting Capacity by Violation Type

Over-Voltage
Under-Voltage
Line Loading
Xfmr Loading
Multiple Violations

Locational Hosting Capacity (MW)

Percent of Locations (%)

PV Size (MW)
12 kV, 9.25 MW peak load
Max daytime load = 8.92 MW (97%)
Min daytime load = 1.96 MW (19%)

Bottom of Band bus voltages average 1.69 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type
12 kV, 8.44 MW peak load
Max daytime load = 8.29 MW (98%)
Min daytime load = 1.13 MW (13%)

Bottom of Band bus voltages average 1.83 V lower

PV Impact Signature

Locational Hosting Capacity
12 kV, 6.35 MW peak load
Max daytime load = 6.29 MW (99%)
Min daytime load = 0.85 MW (13%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 2.34 V lower

PV Impact Signature

Locational Hosting Capacity
12 kV, 6.39 MW peak load
Max daytime load = 5.79 MW (91%)
Min daytime load = 1.52 MW (24%)

PV Impact Signature

Locational Hosting Capacity
12 kV, 5.00 MW peak load
Max daytime load = 4.92 MW (98%)
Min daytime load = 1.95 MW (39%)

Bottom of Band bus voltages average 1.17 V lower

PV Impact Signature

Locations at Each PV Size With Violations (%) vs. PV Size (MW)

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

Legend:
- Over-Voltage
- Under-Voltage
- Line Loading
- Transformer Loading
- Multiple Violations

Legend:
- Peak Daytime Load
- Min Daytime Load

Legend:
- Percent of Locations (%)
CV1

12 kV, 4.29 MW peak load
Max daytime load = 4.00 MW (93%)
Min daytime load = 1.13 MW (26%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 1.36 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

Histogram of Violation Determining Locational Hosting Capacity
12.47 kV, 3.43 MW peak load
Max daytime load = 3.20 MW (93%)
Min daytime load = 1.01 MW (28%)

Locational Hosting Capacity

PV Impact Signature

Locational Hosting Capacity

Voltage Profile: Basecase without PV
Max Daytime Load - Top Of Band
Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 1.90V lower

Hosting Capacity
No Violations
Only Voltage
Only Thermal
Multiple

Over-Voltage
Under-Voltage
Line Loading
Transformer Loading
Multiple Violations

Histogram of Locational Hosting Capacity by Violation Type

Histogram of Violation Determining Locational Hosting Capacity

Scenarios at Each PV Size With Violations (%)
PV Size (MW)

Locations at Each PV Size With Violations (%)
PV Size (MW)

62
12.47 kV, 6.19 MW peak load
Max daytime load = 5.43 MW (87%)
Min daytime load = 1.75 MW (27%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 1.92V lower

PV Impact Signature

Locational Hosting Capacity

Scenario at Each PV Size With Violations (%)

Hosting Capacity
No Violations
Only Voltage
Only Thermal
Multiple

Histogram of Locational Hosting Capacity by Violation Type

Peak Daytime Load
Min Daytime Load
12.47 kV, 1.71 MW peak load
Max daytime load = 1.63 MW (96%)
Min daytime load = 0.73 MW (40%)

PV Impact Signature

Locational Hosting Capacity
12.47 kV, 0.72 MW peak load
Max daytime load = 0.68 MW (92%)
Min daytime load = 0.37 MW (34%)

Bottom of Band bus voltages average 1.93V lower

PV Impact Signature

Locational Hosting Capacity
12.47 kV, 1.17 MW peak load
Max daytime load = 1.15 MW (98%)
Min daytime load = 0.50 MW (39%)

Bottom of Band bus voltages average 1.86V lower

PV Impact Signature

Locational Hosting Capacity
12.47 kV, 0.93 MW peak load
Max daytime load = 0.92 MW (99%)
Min daytime load = 0.32 MW (27%)

Voltage Profile: Basecase without PV

Bottom of Band bus voltages average 1.85V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

Over-Voltage
Under-Voltage
Line Loading
Transformer Loading
Multiple Violations

Histogram of Violation Determining Locational Hosting Capacity

Locational Hosting Capacity (MW)

Percent of Locations (%)
Ckt5

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 0.00V lower

PV Impact Signature

Locational Hosting Capacity
Ckt7

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 0.33V lower

PV Impact Signature

Scenarios at Each PV Size With Violations (%)

Locational Hosting Capacity

Histogram of Violation Determining Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

Host Capacity: No Violations

Over-Voltage

Only Voltage

Only Thermal

Multiple Violations

Percent of Locations (%)
12.47 kV, 6.34 MW peak load
Max daytime load = 5.73 MW (90%)
Min daytime load = 1.04 MW (16%)

Bottom of Band bus voltages average 1.96V lower

PV Impact Signature

Locational Hosting Capacity
12.47 kV, 7.07 MW peak load
Max daytime load = 6.12 MW (86%)
Min daytime load = 2.58 MW (34%)

Bottom of Band bus voltages average 1.90V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

Over-Voltage
Under-Voltage
Line Loading
Transformer Loading
Multiple Violations
12.47 kV, 5.14 MW peak load
Max daytime load = 4.45 MW (86%)
Min daytime load = 1.85 MW (34%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 1.89V lower

PV Impact Signature

Locational Hosting Capacity
UT16

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 1.85V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

12.47 kV, 3.98 MW peak load
Max daytime load = 3.56 MW (89%)
Min daytime load = 1.51 MW (36%)

1.56 km

Histogram of Locational Hosting Capacity by Violation Type

Host Capacity
No Violations
Only Voltage
Only Thermal
Multiple

Locational Hosting Capacity (MW)
Percent of Locations (%)

Over-Voltage
Under-Voltage
Line Loading
Xfmr Loading
Multiple Violations

Scenarios at Each PV Size With Violations (%)

PV Size (MW)

Hosting Capacity
No Violations
Only Voltage
Only Thermal
Multiple

Percent of Locations (%)

Histogram of Locational Hosting Capacity by Violation Type

Percent of Locations (%)

0 10 20 30 40 50 60 70 80 90 100

PV Size (MW)

Hosting Capacity
No Violations
Only Voltage
Multiple

Percent of Locations (%)

Histogram of Violation Determining Locational Hosting Capacity

Percent of Locations (%)

0 10 20 30 40 50 60

Over-Voltage
Under-Voltage
Line Loading
Xfmr Loading
Multiple

Percent of Locations (%)

0 2 4 6 8 10

PV Size (MW)

Any Violations
Over Voltage
Under Voltage
Line Loading
Xfmr Loading

Percent of Locations (%)

0 10 20 30 40 50 60 70 80 90 100

PV Size (MW)

Hosting Capacity
No Violations
Only Voltage
Under Voltage
Line Loading
Xfmr Loading
Multiple

Percent of Locations (%)

0 10 20 30 40 50 60

Over-Voltage
Under-Voltage
Line Loading
Xfmr Loading
Multiple

Histogram of Locational Hosting Capacity by Violation Type

Percent of Locations (%)

0 1 2 3 4 5 6 7 8 9 10+

Locational Hosting Capacity (MW)
12.47 kV, 4.18 MW peak load
Max daytime load = 3.76 MW (89%)
Min daytime load = 1.65 MW (36%)

Bottom of Band bus voltages average 1.88V lower

PV Impact Signature

#### Locational Hosting Capacity
12.47 kV, 2.70 MW peak load
Max daytime load = 2.70 MW (100%)
Min daytime load = 0.86 MW (30%)

Bottom of Band bus voltages average 1.84V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

Histogram of Violation Determining Locational Hosting Capacity
12.47 kV, 5.82 MW peak load
Max daytime load = 5.53 MW (95%)
Min daytime load = 1.65 MW (28%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 2.96V lower

PV Impact Signature

Locational Hosting Capacity
13.2 kV, 4.86 MW peak load
Max daytime load = 4.63 MW (95%)
Min daytime load = 1.38 MW (28%)

Bottom of Band bus voltages average 2.07V lower
CL1

16 kV, 5.87 MW peak load
Max daytime load = 5.21 MW (89%)
Min daytime load = 1.97 MW (33%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 2.09 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Violation Determining Locational Hosting Capacity

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15+
0 20 40 60 80 100
Percent of Locations (%)% Percent of Locations (%)

Over-Voltage Under-Voltage Line Transformer Multiple
Violation Type for Hosting Capacity

% Percent of Locations (%)% Percent of Locations (%)

Over-Voltage Under-Voltage Line Transformer Multiple
Histogram of Locational Hosting Capacity by Violation Type

% Percent of Locations (%)% Percent of Locations (%)

Line Loading Xfmr Loading

Histogram of Locational Hosting Capacity by Violation Type

Peak Daytime Load Min Daytime Load

0 5 10 15 20 30 40 50 60 70 80 90 100
Percent of Locations (%)% Percent of Locations (%)

Over-Voltage Under-Voltage Line Transformer Multiple

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15+
Locational Hosting Capacity (MW)
19.8 kV, 6.93 MW peak load
Max daytime load = 6.93 MW (100%)
Min daytime load = 2.52 MW (36%)
Bottom of Band bus voltages average 2.92V lower

ML1
GL1

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 3.24V lower

PV Impact Signature

Locational Hosting Capacity
GL2

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 3.24V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type

<table>
<thead>
<tr>
<th>PV Size (MW)</th>
<th>Any Violations</th>
<th>Over Voltage</th>
<th>Under Voltage</th>
<th>Line Loading</th>
<th>Xfmr Loading</th>
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<table>
<thead>
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<th>PV Size (MW)</th>
<th>Scenarios at Each PV Size With Violations (%)</th>
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<table>
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<tr>
<th>Locational Hosting Capacity</th>
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<td>Hosting Capacity</td>
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<td>No Violations</td>
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<tr>
<td>Only Voltage</td>
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<td>Only Thermal</td>
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<tr>
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<table>
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<tr>
<th>Histogram of Violation Determining Locational Hosting Capacity</th>
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<tr>
<td>Peak Daytime Load Min Daytime Load</td>
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<tr>
<th>Percent of Locations (%)</th>
<th>Violation Type for Hosting Capacity</th>
<th>Locational Hosting Capacity (MW)</th>
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<td>4</td>
<td>Multiple</td>
<td>5</td>
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</tbody>
</table>

19.8 kV, 2.23 MW peak load
Max daytime load = 2.21 MW (99%)
Min daytime load = 1.28 MW (56%)
**GL3**

**19.8 kV, 2.61 MW peak load**
- Max daytime load = 2.39 MW (91%)
- Min daytime load = 1.08 MW (40%)

**Voltage Profile: Basecase without PV**
- Bottom of Band bus voltages average 3.17V lower

**PV Impact Signature**

**Locational Hosting Capacity**

**Histogram of Violation Determining Locational Hosting Capacity**

**Locational Hosting Capacity by Violation Type**
19.8 kV, 2.51 MW peak load
Max daytime load = 2.38 MW (95%)
Min daytime load = 1.62 MW (63%)
Bottom of Band bus voltages average 3.19V lower
19.8 kV, 3.97 MW peak load
Max daytime load = 3.86 MW (97%)
Min daytime load = 1.91 MW (47%)

Bottom of Band bus voltages average 3.24V lower

PV Impact Signature

Locational Hosting Capacity
GL6

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 3.25V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type
19.8 kV, 2.86 MW peak load
Max daytime load = 2.85 MW (99%)
Min daytime load = 2.16 MW (75%)

Voltage Profile: Basecase without PV
Max Daytime Load - Top Of Band
Min Daytime Load - Top Of Band
Bottom of Band bus voltages average 2.48 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Violation Determining Locational Hosting Capacity
19.8 kV, 5.55 MW peak load
Max daytime load = 5.53 MW (99%)
Min daytime load = 4.23 MW (75%)

Bottom of Band bus voltages average 2.47 V lower

PV Impact Signature

Locational Hosting Capacity
19.8 kV, 5.06 MW peak load
Max daytime load = 5.05 MW (100%)
Min daytime load = 3.61 MW (70%)

Bottom of Band bus voltages average 2.46 V lower

PV Impact Signature

Histogram of Locational Hosting Capacity by Violation Type

Locational Hosting Capacity

Scenarios at Each PV Size With Violations (%)

PV Size (MW)

0 5 10 15

0 10 20 30 40 50 60 70 80 90 100

Any Violations
Over Voltage
Under Voltage
Line Loading
Xfmr Loading

Hosting Capacity
No Violations
Only Voltage
Only Thermal
Multiple

Percent of Locations (%)

0 10 20 30 40 50 60 70 80 90 100

0 5 10 15 15+

Peak Daytime Load
Min Daytime Load

Line Loading

Histogram of Violation Determining Locational Hosting Capacity

Over-Voltage Under-Voltage Line Transformer Multiple

Locational Hosting Capacity (MW)

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15+
19.8 kV, 7.40 MW peak load
Max daytime load = 7.21 MW (97%)
Min daytime load = 1.03 MW (14%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 2.49 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Violation Determining Locational Hosting Capacity
90 kV, 18.63 MW peak load
Max daytime load = 16.91 MW (91%)
Min daytime load = 4.96 MW (27%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 1.28 V lower

PV Impact Signature

Locational Hosting Capacity
20.78 kV, 16.71 MW peak load
Max daytime load = 16.08 MW (96%)
Min daytime load = 6.23 MW (37%)

Voltage Profile: Basecase without PV
Bottom of Band bus voltages average 1.46 V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Locational Hosting Capacity by Violation Type
33 kV, 16.48 MW peak load
Max daytime load = 15.84 MW (96%)
Min daytime load = 5.11 MW (31%)

Bottom of Band bus voltages average 0.99 V lower

PV Impact Signature

Locational Hosting Capacity
Ckt24

34.5 / 13.2 kV (34.5 kV analyzed), 28.45 MW peak load
Max daytime load = 28.45 MW (100%)
Min daytime load = 6.06 MW (21%)

Voltage Profile: Basecase without PV

Max Daytime Load - Top Of Band

Min Daytime Load - Top Of Band

Bottom of Band bus voltages average 2.94V lower

PV Impact Signature

Locational Hosting Capacity

Histogram of Violation Determining Locational Hosting Capacity

Peak Daytime Load
Min Daytime Load

Histogram of Locational Hosting Capacity by Violation Type
6. CONCLUSION

An advanced PV hosting capacity simulation tool is developed and used to quantify system impacts for many PV interconnection scenarios, configurations, and locations. The advanced tools quantify location-specific impacts and the locational hosting capacity of potential PV interconnection locations on the feeder, including PV impact signatures and zones. A set of 50 different real distribution systems is analyzed in detail to demonstrate the range of scenarios and impacts that can occur depending on the feeder characteristics and topology.
7. REFERENCES


<table>
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<tr>
<th></th>
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<th>Robert J. Broderick</th>
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