The Thesis Committee for David Orn Jonsson
Certifies that this is the approved version of the following thesis:

Conservative Estimation of Overvoltage-based PV Hosting Capacity

APPROVED BY
SUPERVISING COMMITTEE:

Supervisor:

Surya Santoso

W. Mack Grady

Conservative Estimation of Overvoltage-based PV Hosting Capacity

by

David Orn Jonsson, B.Sc.

Thesis

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Abstract

Conservative Estimation of Overvoltage-based PV Hosting Capacity

David Orn Jonsson, M.S.E.
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Supervisor: Surya Santoso

The primary objective of this work is to develop and demonstrate the implementation of steady-state stochastic simulation method to estimate a conservative PV hosting capacity of a given distribution, based on the ANSI voltage regulation standard. The work discusses the key factors that determine the voltage rise due to distributed PV. Load demand analysis is done to determine statistically representative minimum daylight load demand for PV analysis. And lastly, the steady-state, stochastic simulation method is discussed and implemented to estimate the PV hosting capacity for small-scale and large-scale PV deployments.

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Chapter 1
Introduction

Hosting capacity is defined as the maximum amount of distributed generation that can be accommodated without violating system operation under existing control and infrastructure. Distribution systems need to adhere to strict operating parameters that include maintaining voltage regulation, power quality, system protection, reliability, etc. The operating conditions of such systems may be negatively affected by the introduction of large amounts of distributed generation, which may cause a violation of normal operating conditions.

The strictest limiting factor and the most undesirable effect of a distribution circuit's PV hosting capacity is often found to be voltage regulation [1]. The national standard for voltage regulation in the United States is set by the ANSI voltage regulation standard C84.1 [2], which states that under normal operating conditions voltage levels should not exceed 1.05 per-unit. The amount of power generated by distributed PV with a distribution circuit can be increased until a violation of the ANSI voltage regulation standard is reached. Once the threshold is reached no more PV generation can be accommodated; (see Figure 1-1).

The primary objective of this work is to develop and demonstrate a simulation method to estimate the PV hosting capacity of a given distribution circuit. The method is influenced by research sponsored by the Electric Power Research Institute, discussed in [2]. The PV hosting capacity will be based on the ANSI voltage regulation standard, which defines the overvoltage limit as 1.05 per-unit.

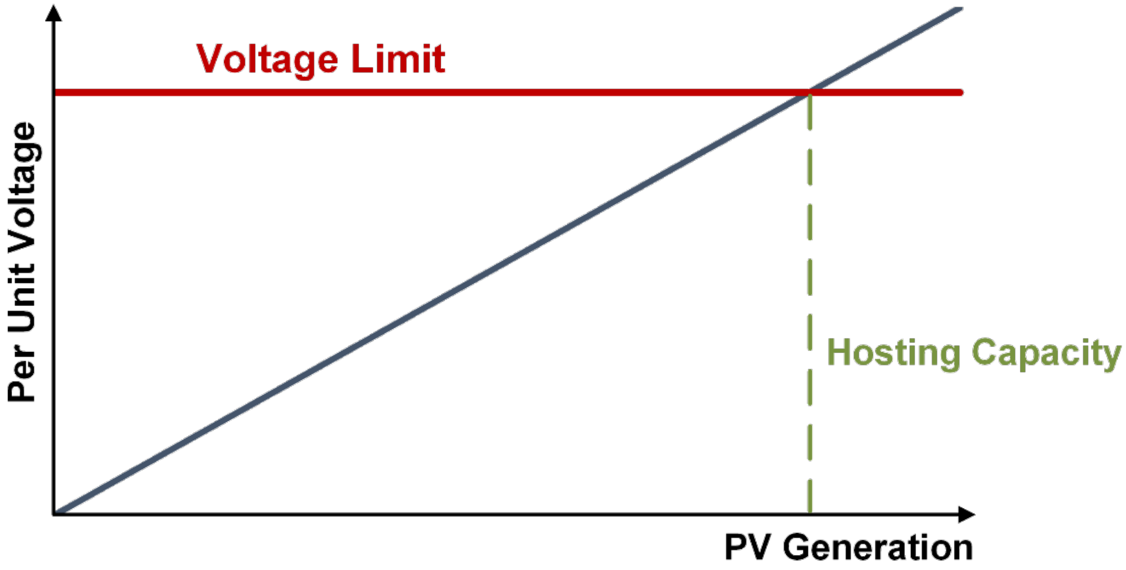

Figure 1-1
PV Hosting Capacity Based on Voltage Regulation

The impact of distributed PV generation on voltage magnitudes of a distribution circuit is discussed in Chapter 2. Through the analysis of a simple two-bus system, the chapter discusses how distributed PV generation impacts the voltage magnitude of the system and which factors are the main cause the voltage rise effect of distributed PV.

In Chapter 3 the distribution circuit for which the PV hosting capacity is to be determined. Following a short description of the circuit characteristics and topology, the chapter describes the determination of active control elements settings and of accurate load parameters consistent with worst-case PV hosting capacity.

Chapter 4 and Chapter 5 both discuss the steady-state, stochastic simulation method. Chapter 4 focuses on small-scale PV deployments while Chapter 5 focuses on large-scale PV deployments. Both chapters show how to implement the method and provide an analysis of the results and determine the PV hosting capacity for each deployment.

Chapter 2
Impact of Distributed PV Generation on Distribution Circuits

2.1 IMPACT OF DISTRIBUTED PV ON A TWO-BUS SYSTEM

A simple two bus system (see Figure 2-1) consists of an infinite source bus (Bus 1) and a load bus (Bus 2), connected together through a short-model transmission line with impedance $\mathrm{R} + j\ \mathrm{X}$ pu. Bus 2 is connected to a constant power load, absorbing $\mathrm{P_L} + j\ \mathrm{Q_L}$ pu. Also connected to the load bus is a PV system that provides a power injection of$\mathrm{P_{PV}}$ pu, to the bus at unity power factor offsetting some or even all the power absorbed by the load. The current, $\hat{I}$, flowing through the transmission line is determined by the constant power load and the amount of power generated by the PV system and expressed as:

$$\hat{I} = conj\left(\frac{(P_L - P_{PV}) + j\ Q_L}{V_2\angle\delta_2}\right) = \frac{(P_L - P_{PV}) - j\ Q_L}{V_2\angle -\delta_2} \tag{2.1}$$

The voltage at the load bus is determined by subtracting the voltage drop over the transmission line from the source bus voltage:

$$\begin{aligned} V_2\angle\delta_2 &= V_1\angle\delta_1 - (R + j\ X)\times\hat{I} \\ &= V_1\angle\delta_1 - (R + jX)\times\frac{(P_L - P_{PV}) - j\ Q_L}{V_2\angle -\delta_2} \end{aligned} \tag{2.2}$$

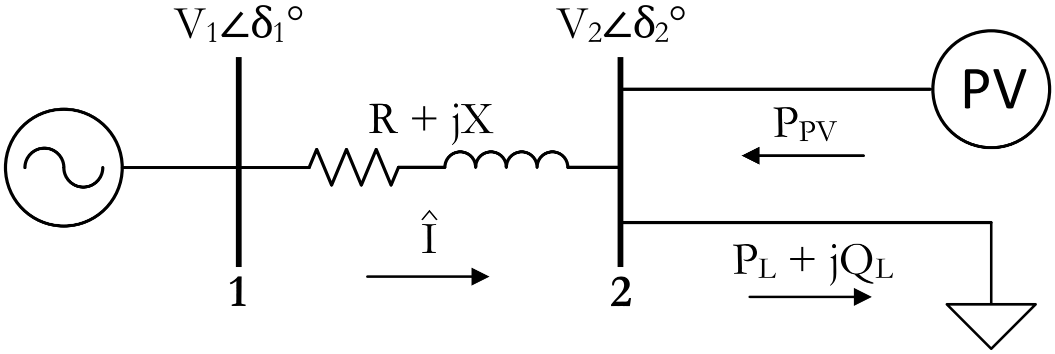

Figure 2-1
Two-bus Power System

In distribution circuits the angular difference between the source bus and load buses is very small and can be neglected with minimal error[1] [3]. This infers a purely real voltage drop over the line impedance i.e. $|V_1 - V_2| \cong \Re\{(R + jX)\times\hat{I}\,\}$. Neglecting the angular difference, (2.3) can be expressed as:

$$\begin{aligned} |V_2| &= |V_1| - \frac{R\times(P_L - P_{PV}) + X\times Q_L}{|V_2|} \\ &= |V_1| - \frac{R\times P_L}{|V_2|} + \frac{R\times P_{PV}}{|V_2|} - \frac{X\times Q_L}{|V_2|} \end{aligned} \tag{2.3}$$

The approximate voltage drop of the two-bus system is given by (2.3) and, unsurprisingly, shows that the main factors contributing to the voltage drop are the line impedance and the net load on Bus 2. An increase in PV generation at the load bus leads to less current flowing from Bus 1 to Bus 2, which offsets the voltage drop by reducing the I^2R line losses. As the PV generation increases, the voltage drop can become negative (i.e. the flow of real power reverses direction) and the voltage magnitude at the load bus becomes larger than at the source bus. This occurs when the conditions of (2.4) are met.

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[1] When no real power flows through the line, i.e. when P_{pv} is equal to P_L, the error should approach zero.

$$R \times P_{PV} > R \times P_L + X \times Q_L \tag{2.4}$$

The Marginal Voltage Magnitude at the Load Bus

The marginal voltage magnitude of the load bus measures the sensitivity of the voltage magnitude to changes in the power injected by the PV system. It is calculated by taking the partial derivative of the load bus voltage magnitude, (2.4), with respect to P_{PV}.

$$\frac{\partial |V_2|}{\partial P_{PV}} = \frac{R}{|V_2|} \tag{2.5}$$

The marginal voltage magnitude, (2.5), indicates that its rate of increase is directly proportional to the line resistance if all other values are equal. The line resistance itself is a function of length, among other things, and therefore it may also be inferred that a long line with high resistance will experience a larger increase in voltage than would a short line with smaller resistance.

2.2 IMPACT OF DISTRIBUTED PV ON A DISTRIBUTION CIRCUIT

The impact analysis of PV generation on the two-bus system is also valid for multi-bus radial distribution system. The nominal increase in the voltage level caused by the injection of real power by the PV system will be the same on all buses downstream, and the rate at which the voltage magnitude increases will still proportional to the resistance upstream, i.e. the source resistance where the PV is connected. High voltage level distribution circuits and transmission lines usually have a high X/R ratio, and, since the rate of change of the voltage magnitude is only proportional to the real part of the source impedance, they are less affected than medium or low level distribution circuits [5].

The impact of distributed PV generation on voltage levels in distribution circuits does not just depend on the amount of power it generates or where it is located. It also depends on system conditions at any given time. The voltage magnitude of the load bus in the two-bus system was given by (2.3) and it shows that the largest possible voltage increase will occur at no-load conditions and full output from the PV system. In practical terms this means that the most conservative estimate of PV hosting capacity is found at minimum load conditions with full output from PV systems.

The impact of PV hosting on voltage magnitudes in the distribution circuit depends on the size and location of the PV system(s) and load demand levels. A conservative estimate of the hosting capacity is found based on worst-case conditions, when load demand is low and PV output is high.

Chapter 3
Distribution Circuit Model

3.1 TOPOLOGY AND CIRCUIT CHARACTERISTICS

A one-line diagram of the given distribution circuit is shown Figure 3-1, modeled in OpenDSS [5]. A single substation serves the entire circuit and its primary operates at a nominal voltage of 12.47 kV. The circuit contains 1,854 buses, of which 639 are primary buses and 1,215 are secondary buses. All secondary buses are load-serving buses, either three-phase or single-phase, operating at voltage levels below 480 V. No loads are connected to the primary wire. A single line regulator – located at the substation – serves the entire circuit. The distribution circuit contains seven capacitor banks: one capacitor bank is rated at 900 kvar, and the other six are rated at 600 kvar. Two of the capacitor banks are constant kvar capacitor banks, three are kvar controlled, and two are time controlled.

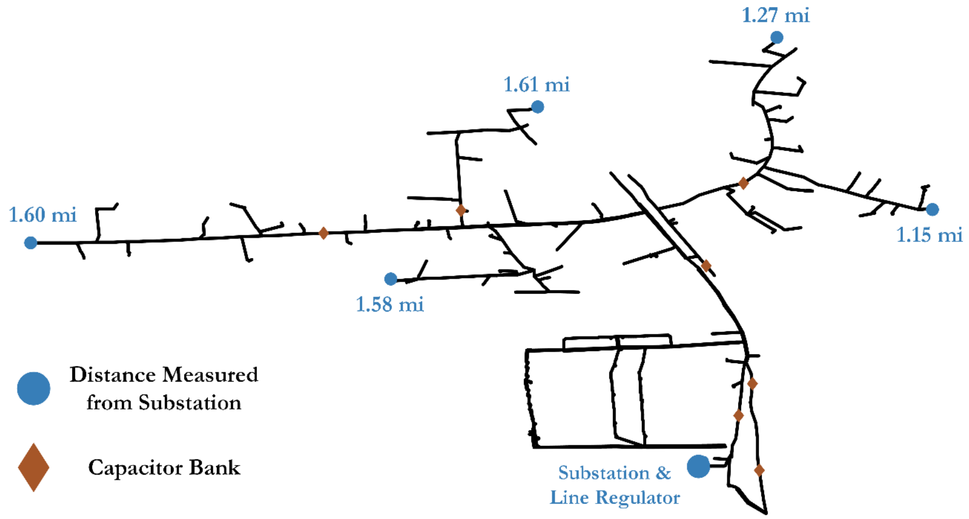

Figure 3-1
One-Line Diagram of the Distribution Circuit.

3.2 EXISTING PV SYSTEMS

Six three-phase PV systems are already installed in the distribution circuit providing a combined output capacity of 1.20 MW. The PV systems are all located some distance away from the substation. The one closest to the substation is also the smallest one with 69 kW of output capacity. The largest individual PV system has a generating capacity of 360 kW and is located at the far end of the circuit. The four remaining ones range in size from 168 kW to 231 kW but are all located far away from substation. Due to their output capacity and location distant from the substation, the existing PV systems might limit further PV penetration in the area surrounding them. The location and the output capacity of each individual PV system within the distribution circuit is shown in Figure 3-2.

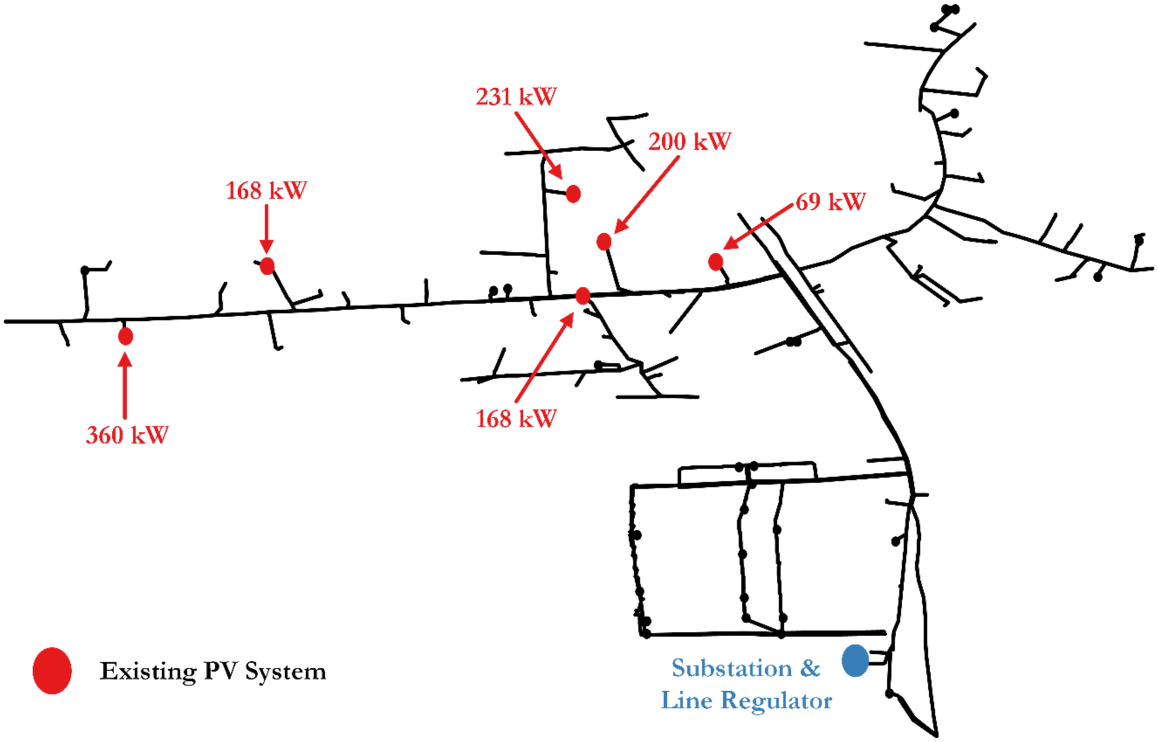

Figure 3-2
Existing PV in the Distribution Circuit

3.3 LOAD DEMAND ANALYSIS

As determined in Section 2.2, load demand is one of the key factors determining the PV hosting capacity of a distribution circuit. Electric loads and distributed PV systems have the opposing effects on voltage magnitudes. The former absorbs power from the circuit while the second provides an injection of power; load demand causes voltage drop while PV systems cause voltage rise. Even though the worst-case PV hosting capacity occurs at no-load conditions that could hardly be called normal operating conditions. Therefore, a more realistic approach is to determine the minimum load demand of the circuit and use that value to determine the PV hosting capacity.

Load Profile of the Distribution Circuit

The load profile of the distribution circuit is shown in Figure 3-3, based on hourly measurements taken at the substation between December 3rd, 2012 and May 30th, 2013. It is important to remember that the circuit has existing PV systems rated at 1.20 MW and as a result the load demand appears lower than it actually is when measured from the substation.

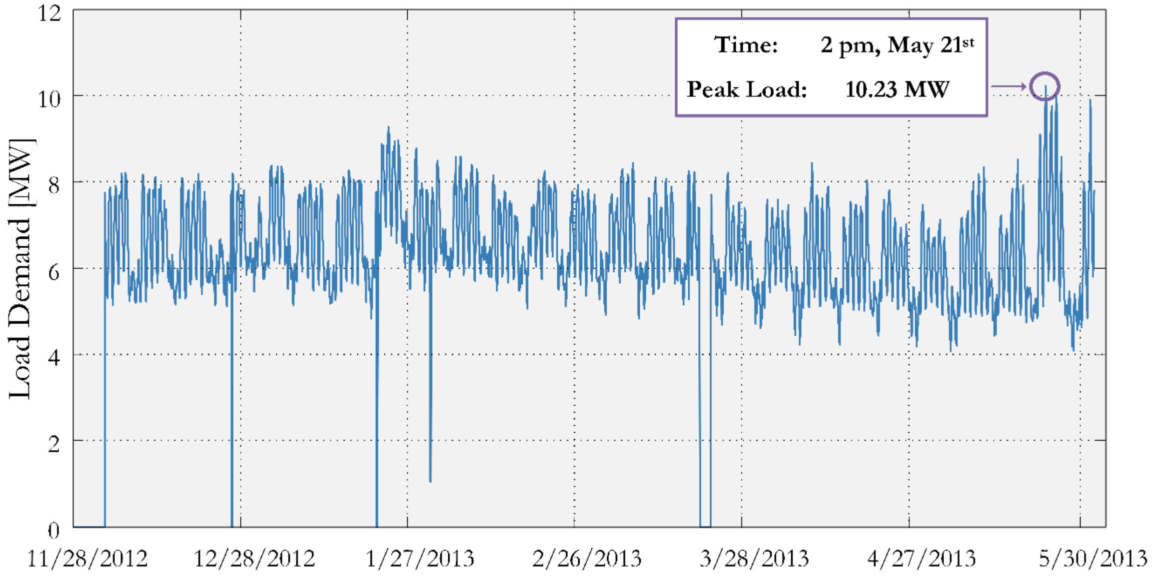

Figure 3-3
Load Profile for December 3rd, 2012 to May 30th, 2013

Determining the Actual Peak Load Demand

By analyzing the load profile in Figure 3-3 it is ascertained that the peak load demand occurred at 2 pm on May 21st, when it reached 10.23 MW. However, since the peak demand occurs during daytime, the existing PV systems are contributing power and thus altering the power flow. As a result, the load demand measured at the substation is not thoroughly representative of the circuit's actual load demand. In order to determine the actual load demand it is necessary to account for and remove the effects of the PV systems. After this adjustment, the actual peak load demand is determined to be 12.50 MW. The load profile, with and without the existing PV systems, is represented in Figure 3-4.

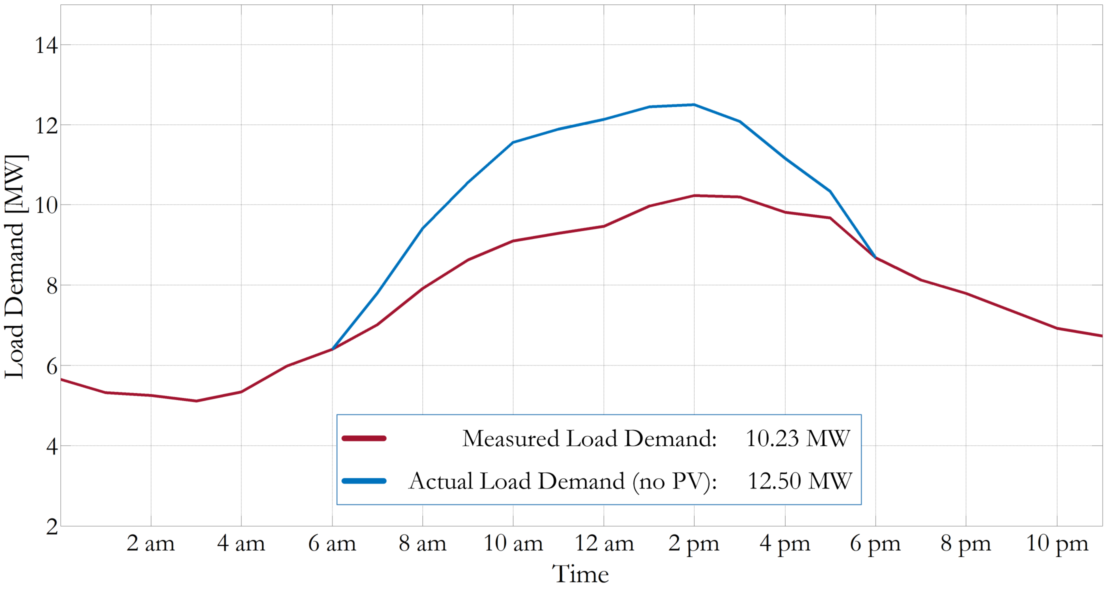

Figure 3-4
Load Demand for May 21st, 2013

Determining Minimum Load Demand during Daylight Hours

Analysis of the load profile (Figure 3-3) shows that minimum load routinely occurs during nighttime. However, load demand during nighttime is not all that helpful when analyzing the impact of a solar-based energy source on distribution circuits. Therefore, acquiring the minimum load demand during daytime requires some additional analysis.

The number of daylight hours can vary quite a lot based on the geographical location, season, and other factors. Fortunately, sunrise and sunset hours over the course of the year are easily accessible online for most locations making it possible to extract the daytime load demand from the total load demand profile.

To obtain minimum load condition for the given distribution circuit, a statistical analysis is carried out on the total load demand. Since the minimum load condition will be used for PV analysis, only the load demand recorded during daylight hours is relevant for the analysis. The monthly average sunrise and sunset hours at the distribution circuit is obtained from 'http://www.sunrisesunset.com', and displayed in Table 3-1. Based on the data in Table 3-1, the hours between 5 am and 8 pm are considered as daylight hours.

Table 3-1
Average Sunrise and Sunset Hours

Month	Average Sunrise Time	Average Sunset Time
Dec,12	7:00 am	5:00 pm
Jan,13	7:00 am	5:00 pm
Feb,13	7:00 am	6:00 pm
March,13	7:00 am	7:00 pm
April,13	6:00 am	8:00 pm
May,13	5:30 am	8:00 pm
June,13	5:30 am	8:30 pm
July,13	5:30 am	8:30 pm
Aug,13	6:00 am	8:00 pm
Sep,13	6:30 am	7:00 pm
Oct,13	7:00 am	6:30 pm

A histogram of the minimum daytime load demand with a bin resolution of 320 kW, is shown in Figure 3-5. Since minimum daytime load demand as low as 2 MW and as high as 10 MW is recorded for a few days, a statistically representative minimum load condition is determined by fitting a Gaussian distribution to the histogram. The statistical representation of the minimum daytime load demand has a mean value of 6.18 MW and a median value of 6.13 MW.

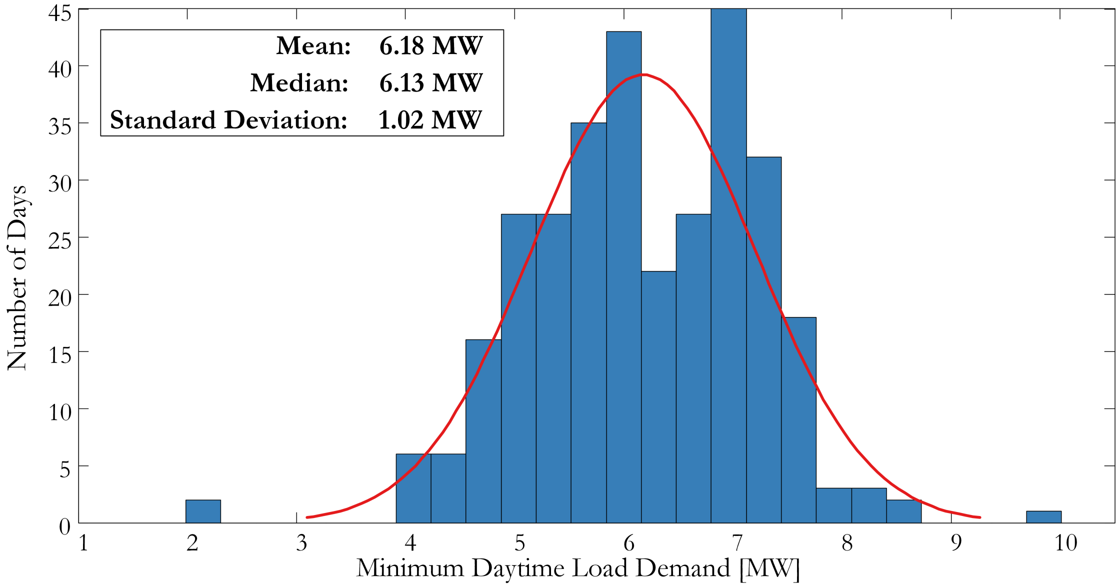

Figure 3-5
Minimum Daytime Load Demand Histogram

The minimum daylight load demand is also explored based on the time of the day it occurred. **Error! Reference source not found.** shows how many times the minimum daylight load demand occurred at each given hour and Table 3-2 shows the average load demand and number of days that minimum load is recorded for a particular time of the day. The minimum load is most frequently recorded in early morning, between 5 am and 7 am, the average minimum load is approximately 6.00 MW, recorded for 198 days. The average minimum load between 6 pm and 8 pm is approximately 6.50 MW, recorded for 50 days. The minimum load is recorded at or near noon for 62 days, coinciding with the time of day PV generation can be assumed to be at or near maximum output.

Based on the statistical analysis above the minimum daytime load for the distribution circuit is estimated as 6.13 MW. This value will be used to find the PV hosting capacity.

Table 3-2
Statistical Analysis of Minimum Daylight Load Demand

Hour of Day	Average Minimum Load	Number of Days
5 am	6.09 MW	78
6 am	6.18 MW	63
7 am	6.69 MW	57
8 am	5.01 MW	3
9 am	**N/A**	0
10 am	4.23 MW	7
11 am	6.03 MW	9
12 am	5.95 MW	15
1 pm	5.71 MW	16
2 pm	5.03 MW	10
3 pm	4.79 MW	5
4 pm	**N/A**	0
5 pm	7.46 MW	2
6 pm	6.84 MW	21
7 pm	6.76 MW	12
8 pm	6.30 MW	17

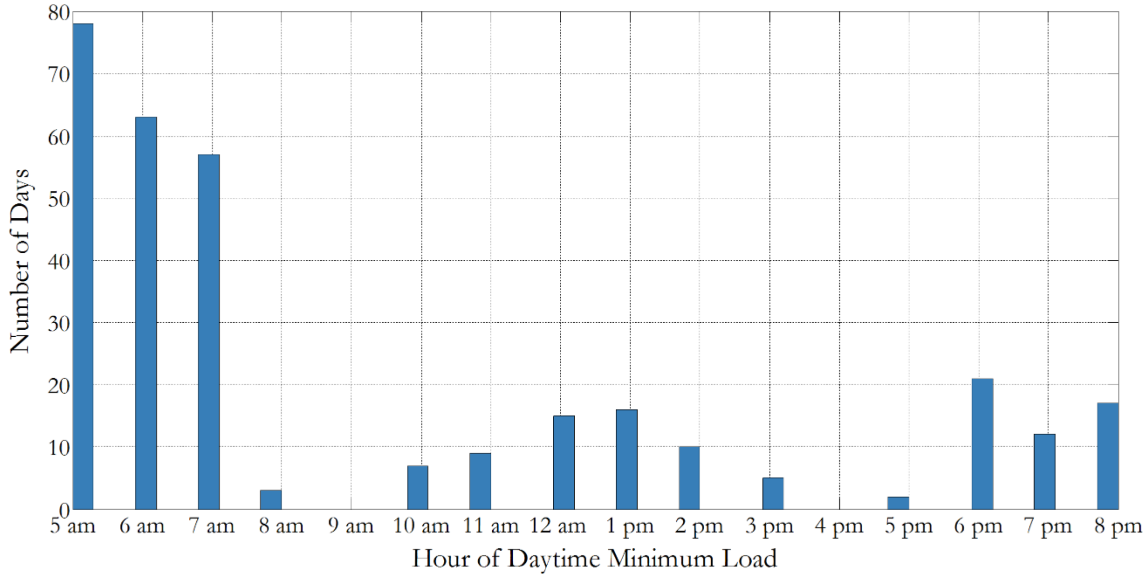

Figure 3-6
Histogram for Hour of the Day when Minimum Load is Recorded

3.4 STEADY-STATE ANALYSIS OF THE DISTRIBUTION CIRCUIT

The last step in setting up the distribution circuit model involves determining the settings of controllable elements in the circuit, the line regulator and capacitor banks. The settings are determined by performing a power flow study at the minimum daylight load conditions with all existing PV systems disabled. Once the power flow has been solved, the settings of the controllable elements are saved and kept constant for all future simulations. Since the existing PV systems do not generate any power, load allocation is based on the actual peak load of 12.50 MW. All load elements are then scaled down to the minimum daylight load demand of 6.13 MW.

The Full Distribution Circuit Model

After having determined the settings of the controllable elements, the full distribution circuit model is completed by again enabling the existing PV. The full circuit model reflects the distribution circuit at the minimum daylight load demand and will be used as the starting point for the steady-state stochastic simulation in Chapter 4 and Chapter 5.

Power Flow Solution for the Distribution Circuit With and Without Existing PV

The power flow solutions for circuit model with and without the existing 1.20 MW, PV systems are presented side-by-side for comparison in Figure 3-7. The figure shows the per-unit voltage magnitude throughout the circuit as a function of distance from the substation. The side-by-side comparison clearly shows how the PV systems impact the circuit by increasing the voltage level. Their capacity is not enough to cause any overvoltage and the maximum voltage magnitude for either solution does not exceed the voltage at the substation.

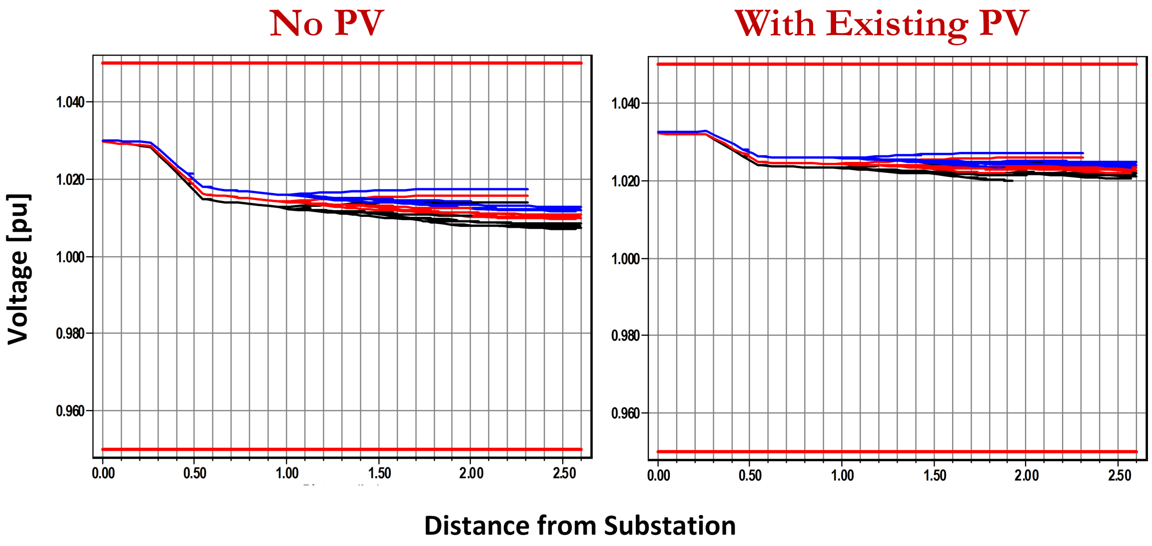

Figure 3-7
Per-unit Voltage Levels With and Without PV at Minimum Daylight Load

Table 3-3
Summary of Distribution Circuit Characteristics

Topology		Load Demand	
Rated Voltage of Primary Wire	12.47 kV	Actual Peak Load Demand[2]	12.50 MW
Rated Voltage of Secondary Wire	0.48 kV	Minimum Daytime Load Demand	6.13 MW
Number of Primary Buses	639	Existing PV Generation	1.20 MW
Number of Customer Loads	1,215		

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[2] Actual Load Demand is the power absorbed by the circuit when all distributed generation has been disabled and is only supplied through the substation.

Chapter 4
Steady-state, Stochastic Simulation for Small-Scale PV Deployment

This chapter discusses PV hosting capacity based on a small-scale, customer level PV deployment. The first half of the chapter describes the small-scale simulation method, which is used to determine the PV hosting capacity of the distribution circuit that was introduced in Chapter 3. The second half of the chapter presents the results and provides an analysis of them.

The steady-state, stochastic simulation method for small-scale PV deployment is described by the flow chart in Figure 4-1. Small-scale PV deployment considers scenarios where PV systems are owned and operated by individual customers, either residential or commercial. These PV systems can be located at any load bus and have varying output capacities. Due to the vast number of different combinations that result from the two random variables, a stochastic simulation is required to simulate as many different PV deployments as possible. The flow chart shows that 100 deployment scenarios are created, with each scenario containing 50 cases with growing amount of distributed PV generation. A power flow solution is obtained for each case, 5,000 in total, in order to check if any overvoltage violation has occurred for the given case.

The method and the individual processes shown in the flow chart are described in more detail in Section 4.1 and Section 4.2. .

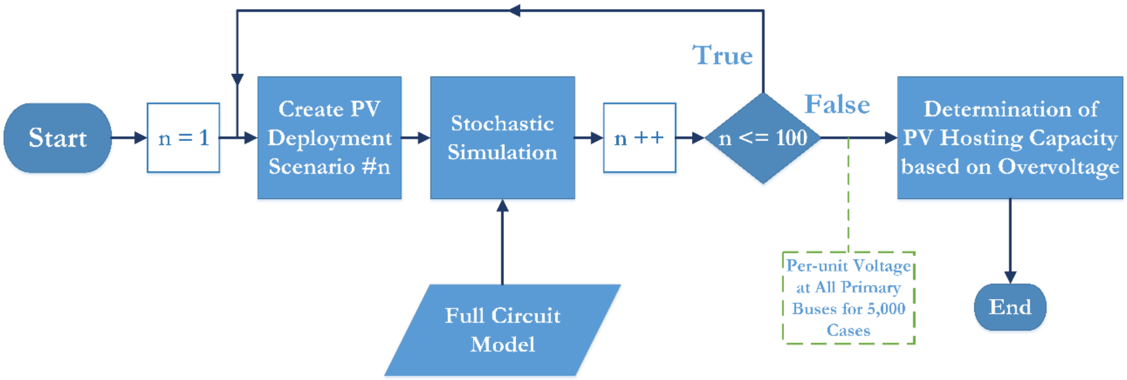


Figure 4-1
Determining PV Hosting Capacity using Steady-state Stochastic Simulation

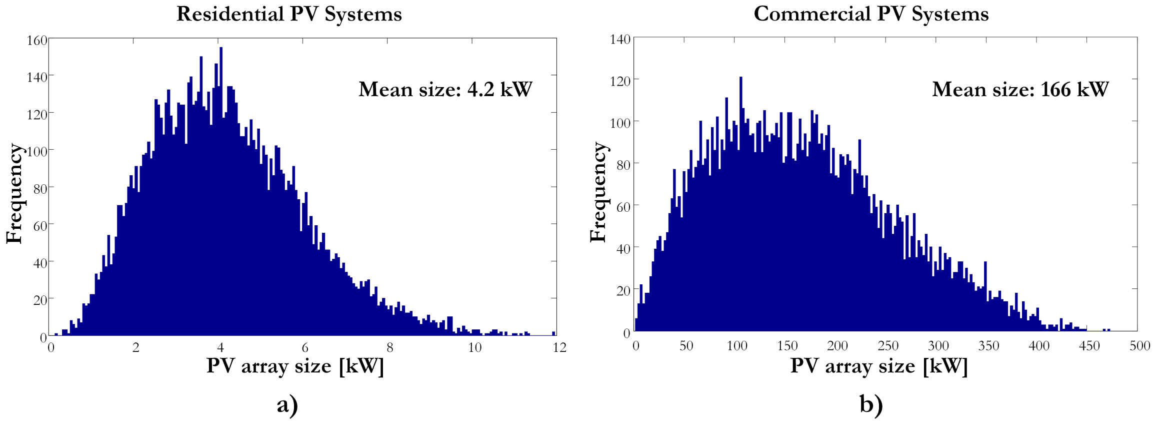
4.1 DEVELOPMENT OF SMALL SCALE PV DEPLOYMENT SCENARIOS

Two random variables factor into the impact of small-scale distributed PV, the power output capacity of the PV systems and their location. The small-scale PV systems are limited in output capacity and it is unlikely that a single one could cause a disruption in normal operating conditions. However, what they lack in size they can make up for in numbers, which is reflected by the 'customer penetration level', defined as the percentage of consumer loads with installed PV. No customer penetration means that no customer load bus has a PV system while at a hundred percent customer penetration level every customer load has one.

Creating a Small-Scale PV Deployment Scenario

A flow chart for the creation of a small-scale PV Deployment Scenario is shown in Figure 4-3. The first step in creating a PV deployment scenario is to collect a list of all potential PV sites; for small-scale deployment this would include all customer load buses. A random draw from the list determines where the first PV system is deployed. Once a load bus has been selected, it becomes ineligible for any further deployment and removed from the list. The output capacity of the PV system is also determined by random draw from either the residential or the commercial distribution function seen in Figure 4-2[3]. The output capacity depends on whether the bus serves a residential or a commercial load, their mean output capacity being 4.2 kW and 166 kW, respectively. The output capacity of the PV system being deployed is limited by the peak load demand of said customer and if the randomly selected output capacity exceeds that value. This procedure is then repeated until full customer penetration level is reached.

Due to the large number of possible combinations when deploying PV systems of varying size amongst the 1,215 load buses in the distribution circuit, multiple PV deployment scenarios are required to catch as many outcomes as possible. For the purpose of this work 100 scenarios are generated.



a)

b)

Figure 4-2
Output Capacity of Small-scale PV systems

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[3] California Solar Initiative Survey [http://www.californiasolarstatistics.org/]

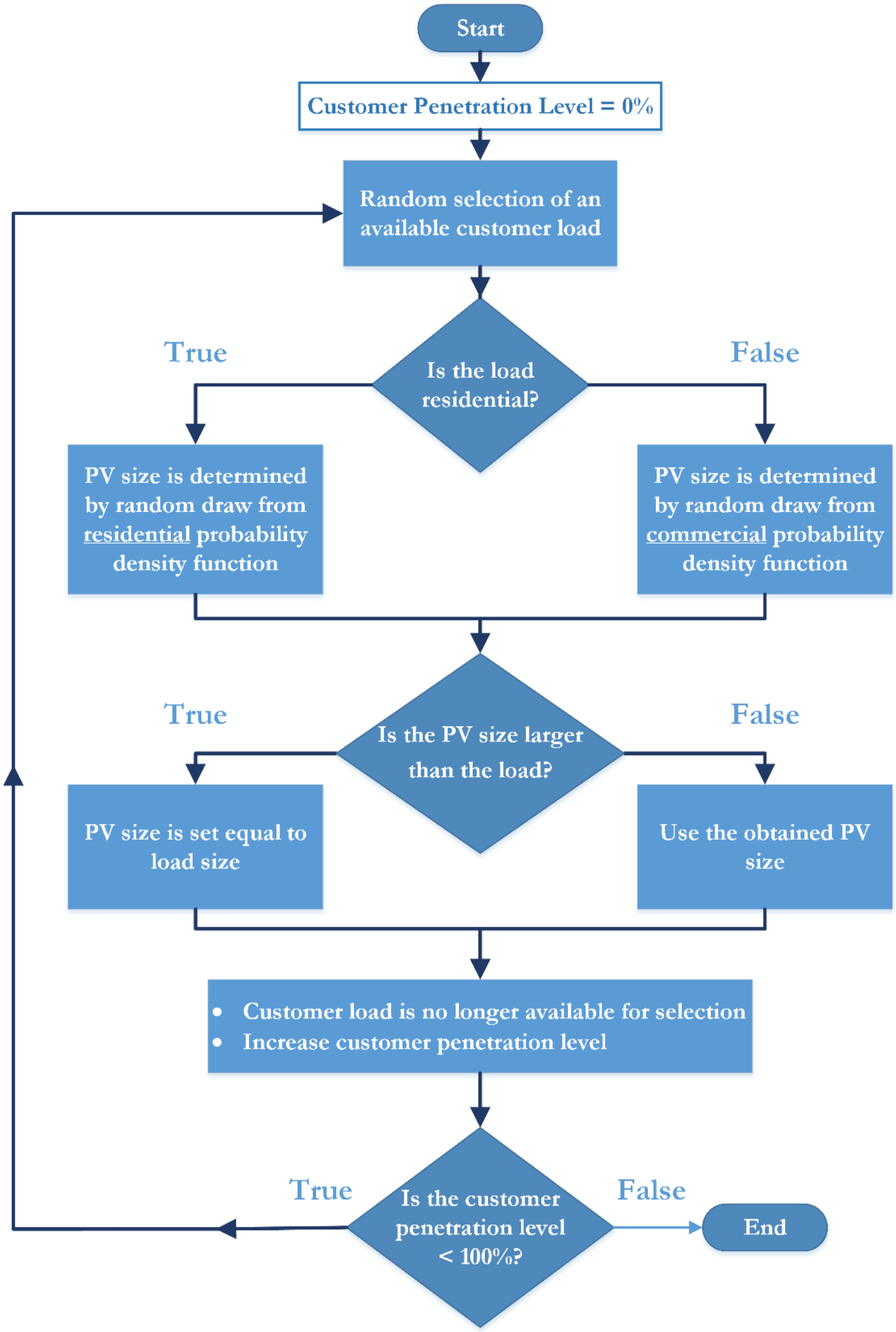


Figure 4-3
Flow Chart for Creating a Small-scale PV Deployment Scenario

4.2 STEADY-STATE STOCHASTIC SIMULATION OF SMALL-SCALE PV DEPLOYMENT

A PV deployment scenario as discussed in Section 4.1, is essentially a list of commands that modify the circuit model by placing a PV system of some certain size at some given bus and in what order. There are 1,215 load buses in the distribution circuit being analyzed, and thus a deployment scenario should contain as many command lines. It would be excessive to compute a power flow solution for each deployed PV system, especially when considering all one hundred deployment scenarios. Therefore, a power flow solution is determined for discrete steps of the customer penetration level. A step size of 2% is chosen, resulting in 50 power flow solutions for each deployment scenario. Hence, with 100 deployment scenarios each one broken up into 50 parts, the small-scale stochastic simulation is solves the power flow for 5,000 permutations of possible PV system placements. This process is described by the flow graph in Figure 4-4

Table 4-1
Number of Small-Scale PV Deployment Simulation Runs

Number of PV Deployment Scenarios	100
Number of Customer Penetration Levels	50
Total Number Of Permutations	5,000

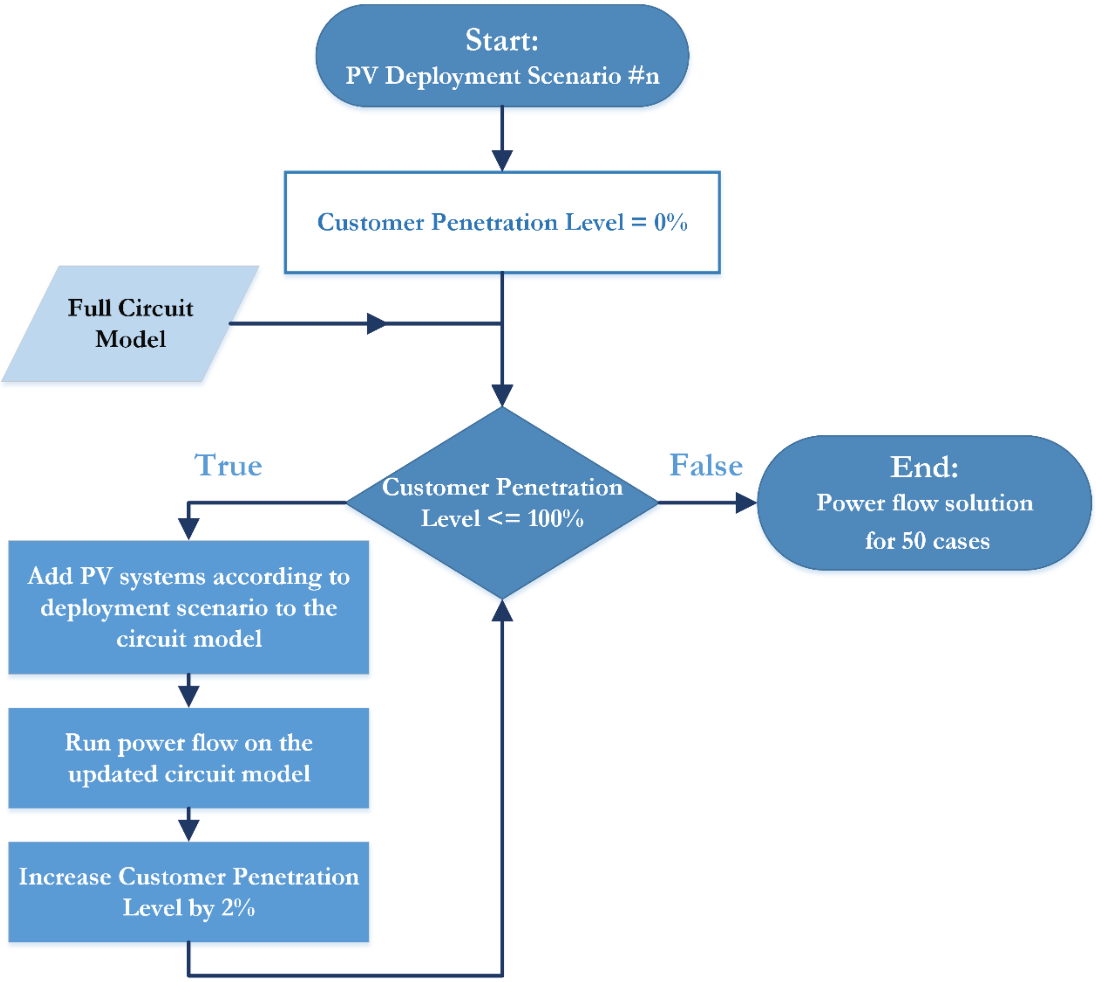


Figure 4-4
Stochastic Simulation of a Single PV Deployment Scenario

4.3 RESULTS FOR SMALL SCALE DEPLOYMENT

The stochastic simulation procedure discussed in Section 4.2 yields the voltage magnitude at every primary bus in the distribution circuit for all 5,000 cases. Both the maximum voltage magnitude and the total power generated by the deployed PV systems, is determined for all 5,000 cases and the resulting data points plotted in Figure 4-5. The figure contains 5,000 data points and shows the maximum voltage magnitude and the amount of distributed PV. An overvoltage violation has occurred if the maximum voltage magnitude exceeds 1.05 per-unit for the given PV generation.

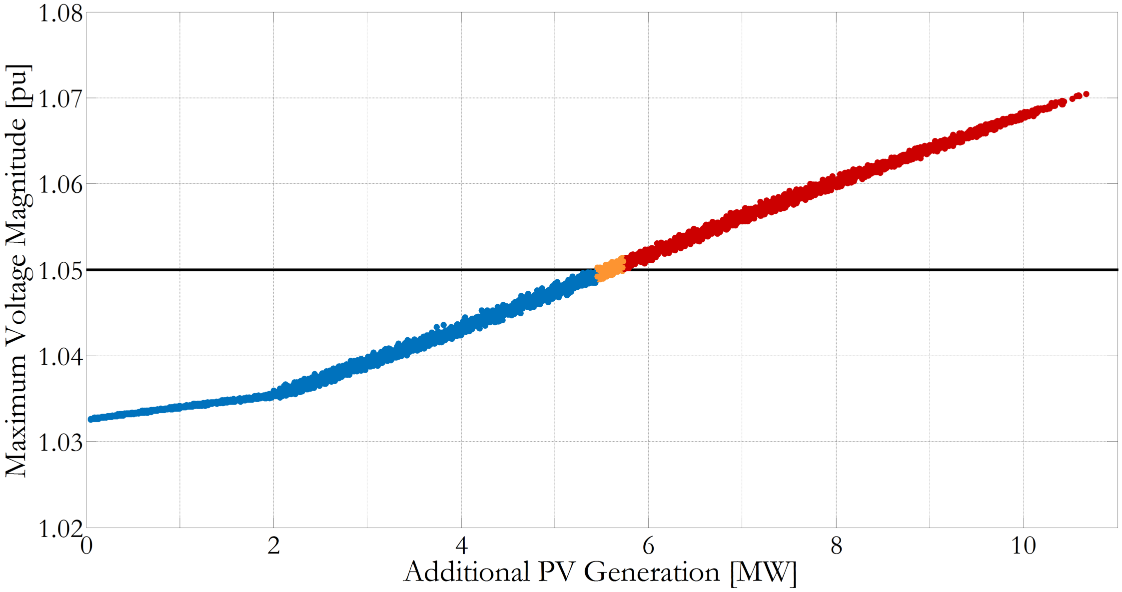


Figure 4-5
Maximum Primary Bus Voltage for Every Small-scale Deployment Case

The data points in Figure 4-5 have been color coded for easier analysis; blue indicates no overvoltage in any scenario, orange indicates that overvoltage occurs in some scenarios but not others, red indicates overvoltage in every scenario.

Despite the random variation in PV deployment, Figure 4-5 indicates a near linear relationship between the maximum voltage in the circuit and the amount of power generated by distributed PV. Notice however, that the slope of the line (the marginal value of the maximum voltage magnitude) increases after ca. 2 MW of distributed PV generation. In a traditional distribution circuit, a single source of power emanates from the substation where the voltage is at its highest. As the power from the substation flows out into the circuit, the voltage level decreases due to losses along the way. With distributed generation in the circuit, less power is needed from the substation, thus lowering those losses and decreasing the voltage drop. When the PV output is less than 2 MW, the maximum voltage magnitude is still centered around the substation and, while the voltage may be rising faster at other locations in the circuit, they are still lower in magnitude. When the PV generation increases beyond 2 MW, the maximum voltage magnitude is no longer at the substation.

Overvoltage and PV Hosting Capacity

The maximum voltage magnitude starts closing in on the ANSI voltage limit as the PV output exceeds 5 MW and the first overvoltage violation occurs at 5.45 MW of PV generation. The first overvoltage happens at the worst PV deployment combination and represents the minimum amount of PV that can be accommodated in the circuit. Different combinations of PV deployment scenarios allow more power to be generated by PV systems without causing an overvoltage violation, and the optimum PV deployment scenario would allow the maximum amount of PV generation without causing a violation. The optimum deployment has been reached when all scenarios cause an overvoltage violation. This occurs when PV systems with combined output of 5.72 MW have been added to the circuit.

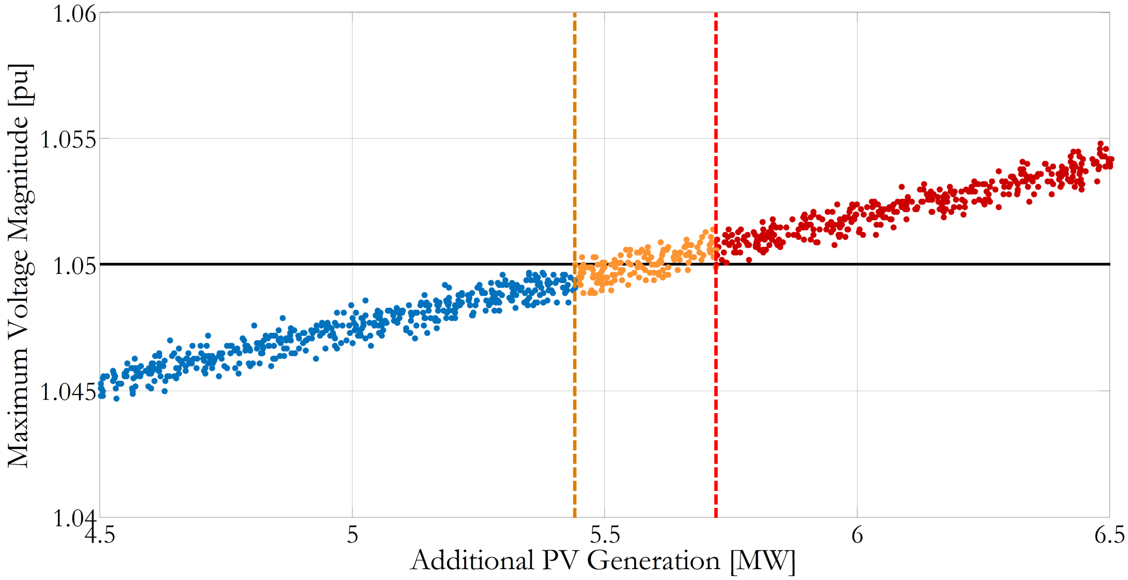


Figure 4-6
Lower and Upper Boundaries of PV Hosting Capacity

4.4 OVERVOLTAGE ANALYSIS FOR SMALL-SCALE PV DEPLOYMENT

The first overvoltage violation occurs at a customer penetration level of 52%. In other words, slightly more than half of all customer loads have been equipped with a PV system, collectively generating a total of 5.44 MW. An overvoltage violation occurs for all deployment scenarios at a customer penetration level of 66%, with net PV generation of 5.72 MW. It is interesting to note that the customer penetration level at the upper boundary is 27% higher than it is at the lower boundary, while the net PV generation is only 5% higher. This disparity is most likely due to the fact that most of the customer loads are residential and thus equipped with a smaller size PV system. A histogram of the PV systems at first overvoltage (Figure 4-7) reveals that the vast majority have output capacities less than 10 kW, also suggesting that most of the loads are residential.

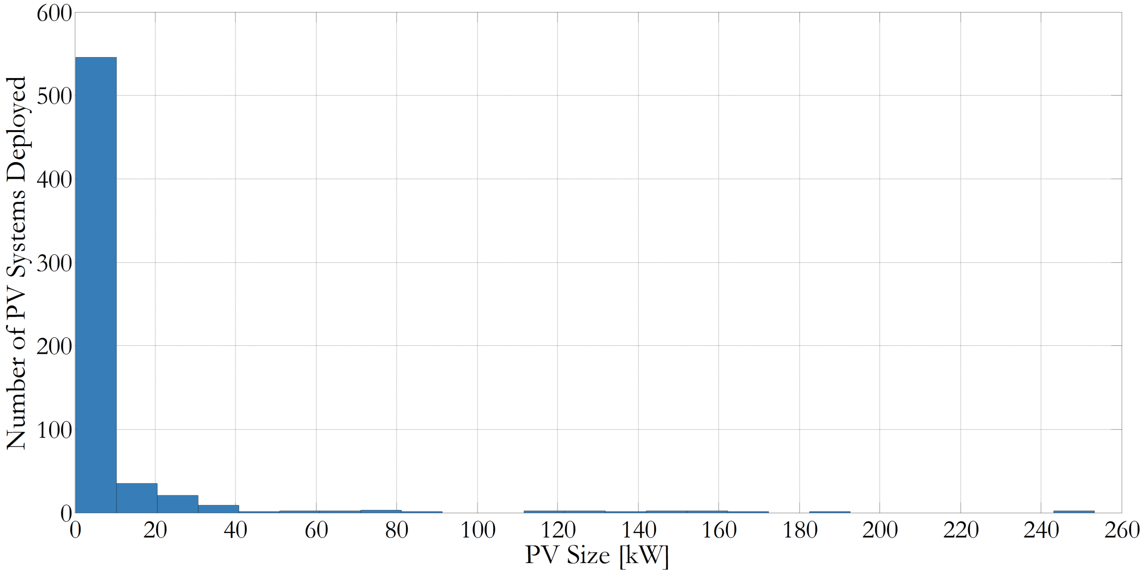


Figure 4-7
Rated Output of PV Systems at First Overvoltage

Circuit Conditions for Upper Boundary and Lower Boundary

The PV deployment and the voltage magnitude along the primary wire are depicted in Figure 4-8 for both the lower and upper limits of the hosting capacity. The PV deployment figure shows the location and type of PV system, residential, commercial, or a previously existing one. The voltage magnitude figure shows the location an overvoltage has occurred; a yellow indicator is placed at a bus when the voltage magnitude is less than 1.05 per-unit while a red one is used to indicate overvoltage.

At the lower boundary, overvoltage violations occur at two primary buses. Both buses are located far away from the substation with a number of commercial PV systems deployed in the surrounding area. At the upper boundary, PV generation has increased by 5%. Even though the PV generation is only 5% higher at the upper boundary, overvoltage spreads throughout the circuit, with most of the unaffected buses located close to the substation.

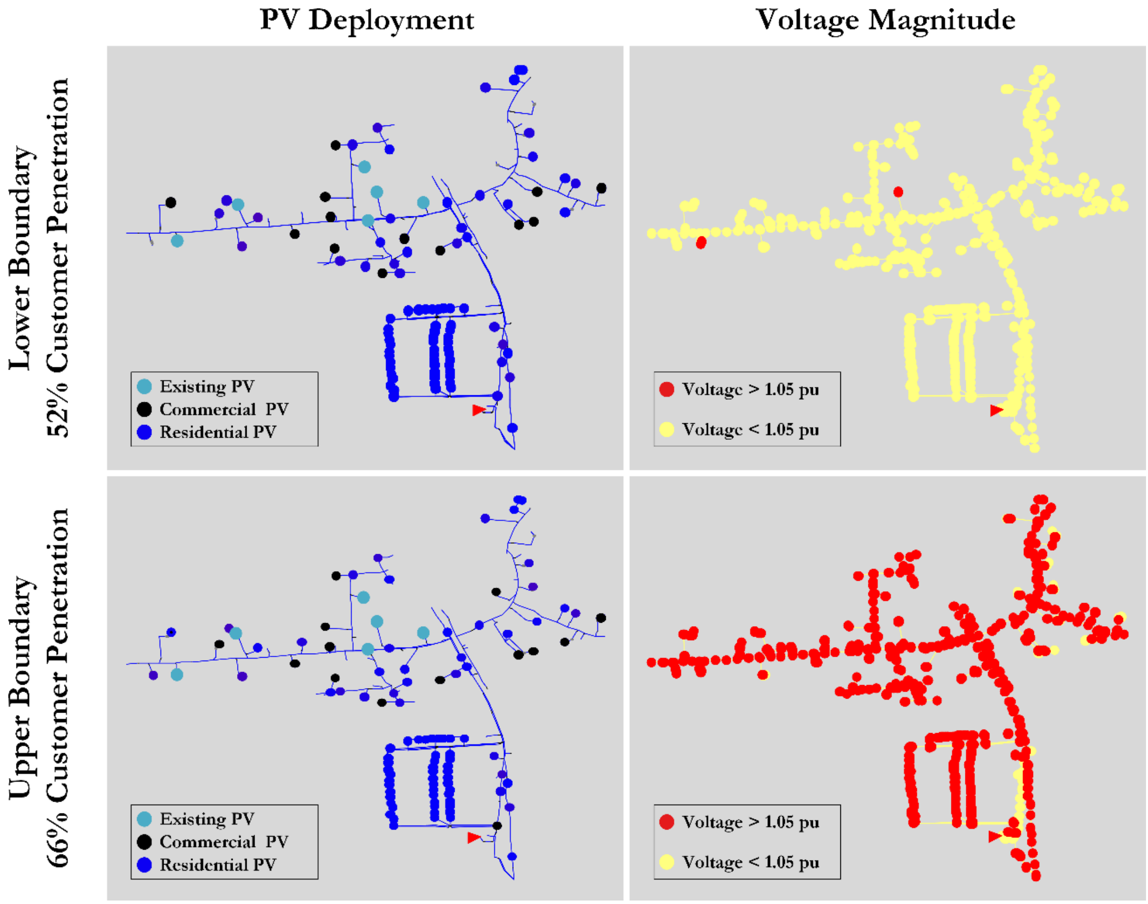


Figure 4-8
PV Deployment and Voltage Magnitudes at Upper and Lower Boundaries

Proliferation of Overvoltage Violations

Figure 4-9 shows the proliferation of overvoltage violations with increasing PV generation. Both the lower and upper boundaries of the PV hosting capacity are plotted in the figure for reference. All 5,000 cases are represented in the figure by a data point that represents the maximum voltage magnitude at a given level of PV generation.

Before the first overvoltage violation, when PV generation is still below 5.54 MW, none of the buses experience overvoltage. At the first overvoltage scenario, two buses experience overvoltage, mirroring the voltage magnitude plot in Figure 4-8. After the first overvoltage violation occurs the number of buses experiencing overvoltage increases at a rapid rate. At the upper boundary of the hosting capacity, some scenarios cause overvoltage at over 200 primary buses while other scenarios with more fortunate PV deployments have spread the overvoltage to only a few buses

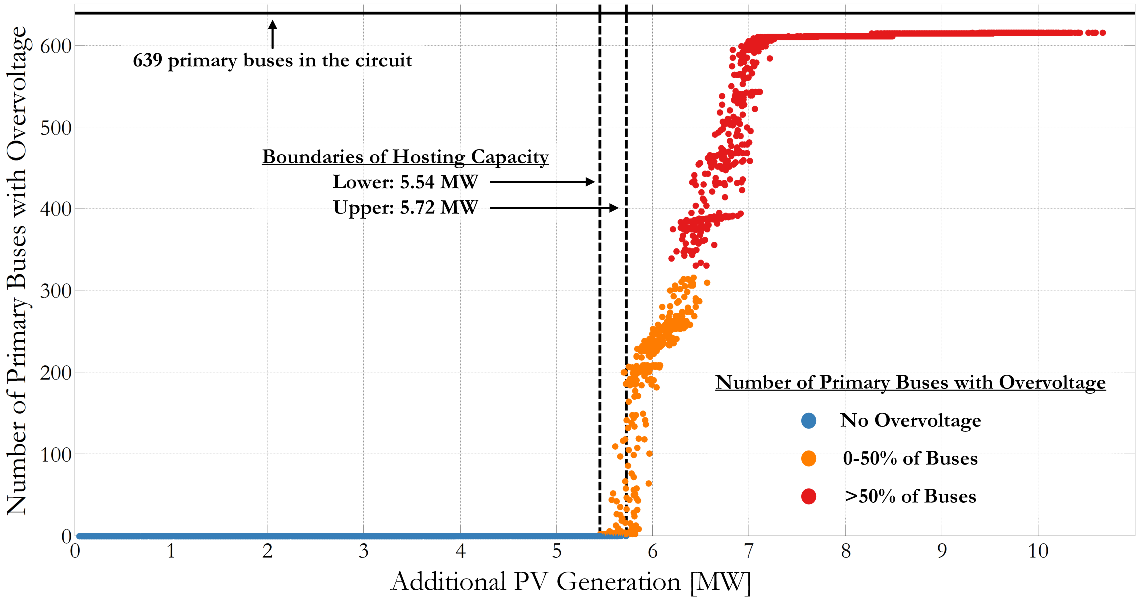


Figure 4-9
Number of Primary Buses with Overvoltage vs. Additional PV Generation

The figure has been color coded to indicate the percentage of primary buses affected by overvoltage. A blue data point indicates that the voltage levels in the circuit are all normal within the limit. The blue data points extend all the way from 0 and up to the upper boundary. When a data point turns orange an overvoltage violation has occurred but less than half of the primary buses have been affected.

The first orange data point is also the first overvoltage scenario. Finally, a red data point means that more than half of the primary buses have an overvoltage violation; the data points start turning red when the PV generation starts growing beyond 6 MW. At 7 MW most of the primary buses have overvoltage but the proliferation of the overvoltage slows down to a near halt. This shows that a few of the primary buses have considerably higher tolerance than the rest and can accommodate large amounts of PV generation. Based on the analytical analysis in Chapter 2, these are likely to be buses close to the substation with low source resistance.

4.5 SUMMARY

The steady-state, stochastic simulation for small-scale PV deployment was implemented to determine the PV hosting capacity of the given distribution circuit based on overvoltage. An analysis of the results revealed that for the worst PV deployment, the circuit has a minimum hosting capacity of 5.44 MW. The maximum hosting capacity was determined as 5.72 MW, occurring at the most optimal PV deployment. These results are shown in Table 4-2.

Table 4-2
PV Hosting Capacity based on Overvoltage

Lower Boundary: **1st Overvoltage Violation**	**5.44 MW**
Upper Boundary: **All Deployments Cause Overvoltage**	**5.72 MW**

Chapter 5
Large-Scale Steady-State Stochastic Models

In Chapter 4 the steady-state stochastic method was applied in order to determine the PV hosting capacity of the distribution circuit assuming PV adoption by residential and commercial customers. In this chapter the same method is applied to determine the hosting capacity based on large-scale, utility operated PV systems. The process–shown in Figure 5-1 is carried out by first developing a suitable PV deployment scenario for large-scale PV simulation. The PV deployment scenario contains instructions for adding PV systems to the distribution circuit model described in Chapter 3. A power flow study is performed after each addition to determine the voltage magnitudes at that step. The PV hosting capacity is then determined based on overvoltage as defined by the ANSI voltage regulation standard.

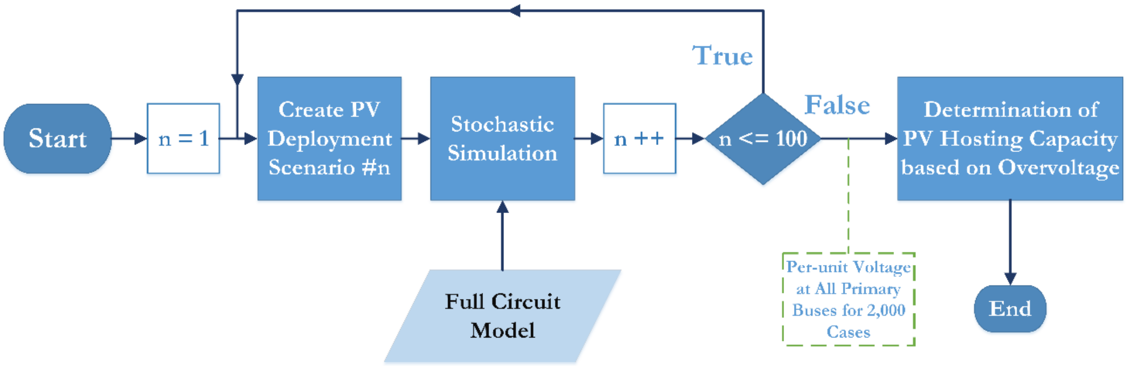


Figure 5-1
Determination of PV Hosting Capacity using Steady-state, Stochastic Simulation

5.1 DEVELOPMENT OF LARGE-SCALE PV DEPLOYMENT SCENARIOS

Large-scale PV systems are most likely owned and operated by utility companies and therefore there is less randomness when it comes to power output and location. PV hosting capacity based on large-scale deployment can help determine if a specific area of a circuit is ill equipped or unable to accommodate distributed PV and is helpful when it comes to avoiding deployment to bad location. Five primary wire buses selected based on likelihood of PV adoption and position in the circuit: one at the substation, two at far-ends, and two in the middle of the feeder, on separate laterals. In addition, three single-phase PV systems are deployed to a part of the feeder containing a large concentration of loads. The six locations selected as possible deployment locations are seen in Figure 5-2.

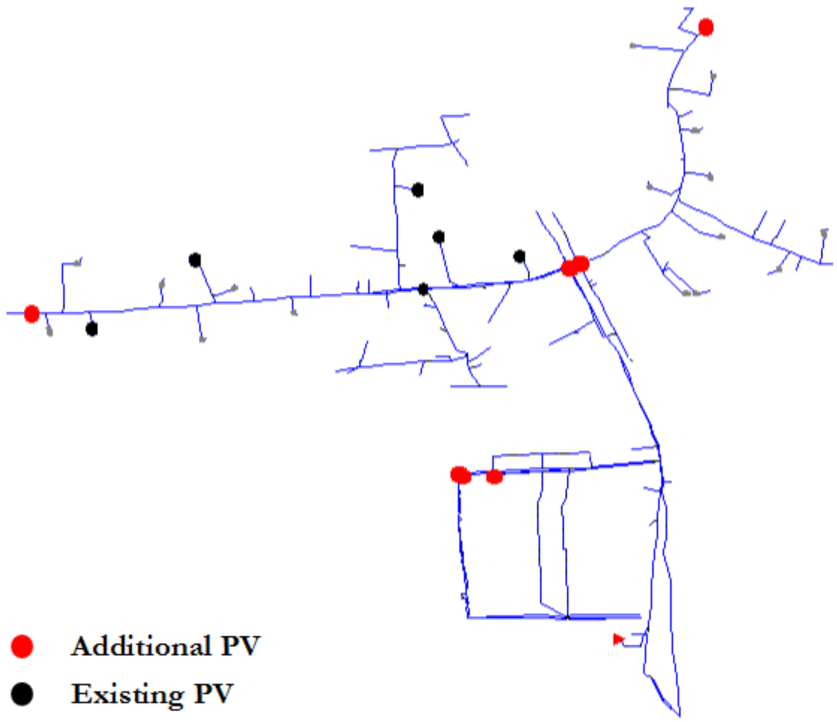


Figure 5-2
Location of PV Systems; both Existing and Selected Bus Locations

Creating a Large-Scale PV Deployment Scenario

A flow chart for the creation of a large-scale PV Deployment Scenario is shown in Figure 5-3. The first step in creating a PV deployment scenario is to collect a list of all potential PV sites; that list only includes the six buses selected for large-scale deployment. A random draw from the list determines the bus to where a PV system is deployed. There is no limit on the number of PV systems that can be deployed to any of the buses. The output capacity of each PV system is constant 0.50 MW. This procedure is then repeated until 20 PV systems, a total of 10 MW have been deployed.

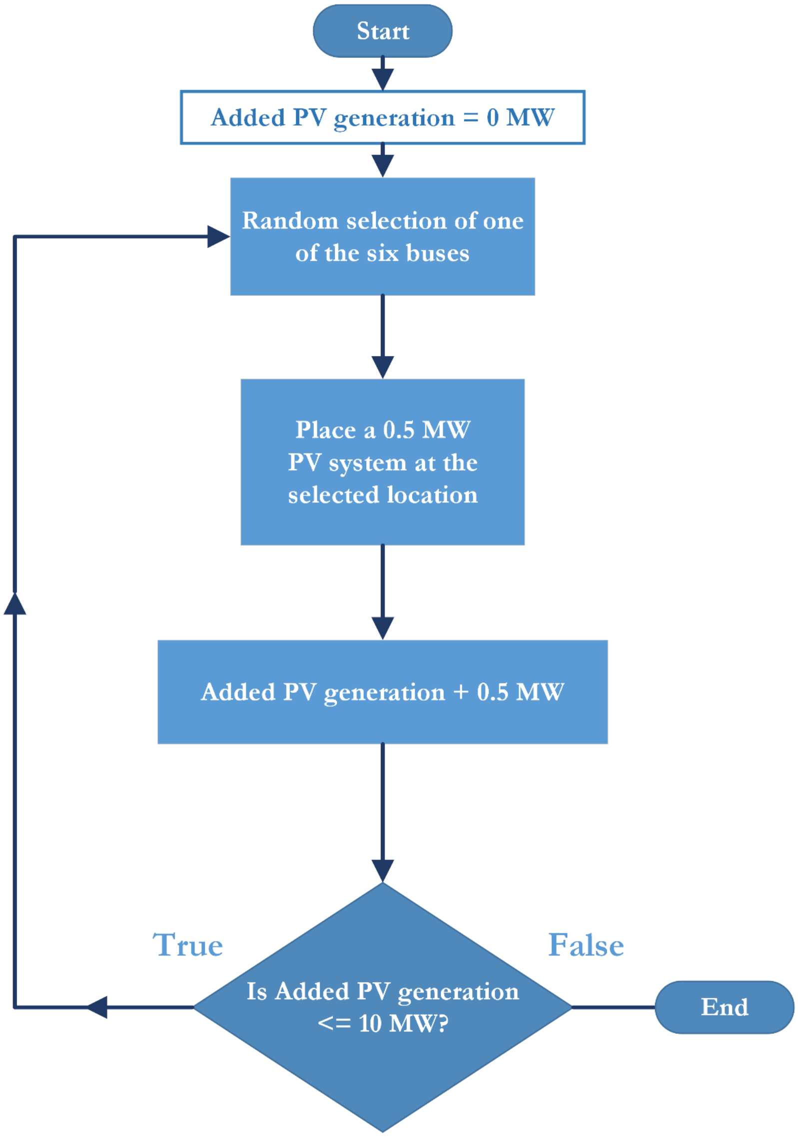


Figure 5-3
Flow Chart for Creating a Large-Scale PV Deployment Scenario

5.2 STOCHASTIC SIMULATION OF LARGE-SCALE DEPLOYMENT

PV systems with output capacity of 0.5 MW are added to the distribution circuit model that was developed in Chapter 3, as specified by each PV deployment scenario. After each deployment a power flow study is performed to determine the circuit's voltage magnitudes resulting in 20 power flow solutions for each deployment scenario. Hence, with 100 deployment scenarios each broken up into 20 parts, the large-scale stochastic simulation is based on 2,000 permutations of possible PV deployments. A flow chart describing the process is shown in Figure 5-4.

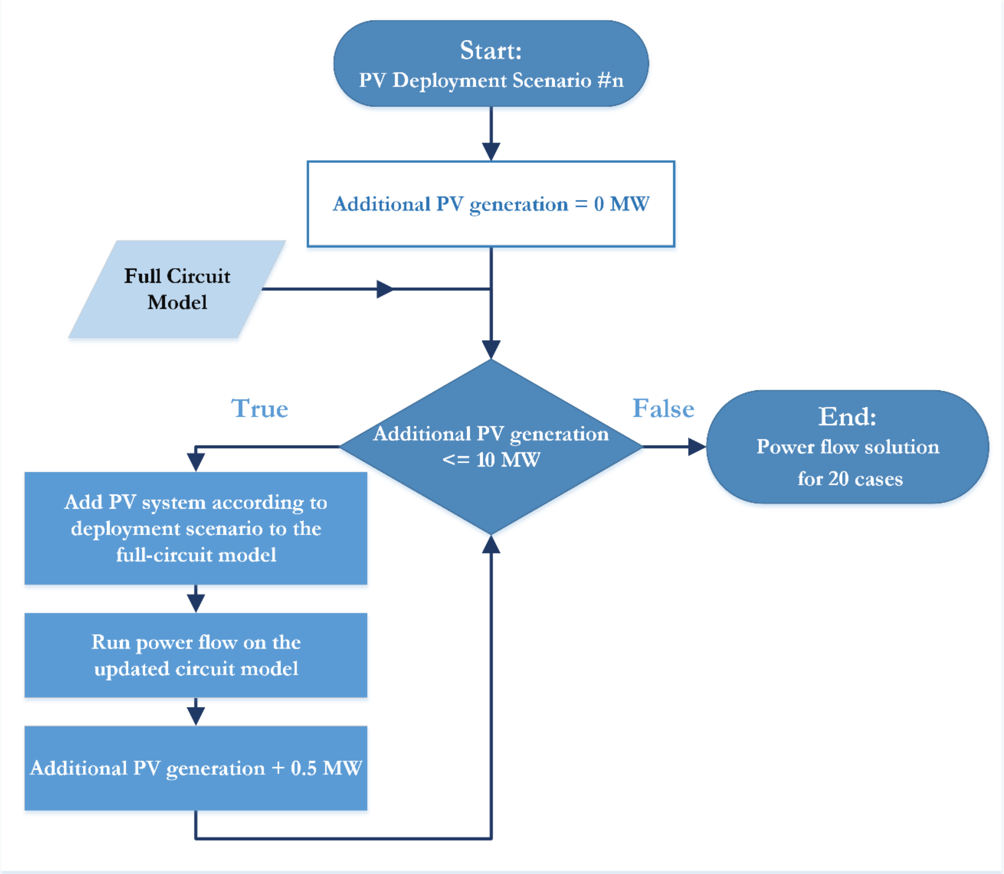


Figure 5-4
Stochastic Simulation of a Single Large-scale PV Deployment Scenario

Table 5-1
Number of Large-Scale PV Deployment Simulation Runs

Number of PV Deployment Scenarios	100
Number of Customer Penetration Levels	20
Total Number of Permutations	2,000

5.3 RESULTS FOR LARGE SCALE DEPLOYMENT

The stochastic simulation provides 2,000 power flow solutions. After determining the maximum voltage magnitude on the primary wire for each case, they can be compared with the ANSI voltage limit of 1.05 per-unit to determine the hosting capacity. The results are shown in Figure 5-5.

Since the size of any deployed PV system is constant, the results of the large-scale stochastic simulation in Figure 5-5 look quite different from the equivalent small-scale results in Figure 4-5; PV generation increases in discrete steps of 0.50 MW instead of being spread out. It can also be noted that the maximum voltage magnitude has a greater disparity than it did for the small-scale simulation and this variance increases with the amount of PV generation. As an example, at 8.00 MW, the maximum voltage magnitude ranges from 1.048 per-unit to 1.062 per-unit for the large-scale simulation, while the range of maximum voltage magnitude for the small-scale simulation at 8.00 MW is almost negligible.

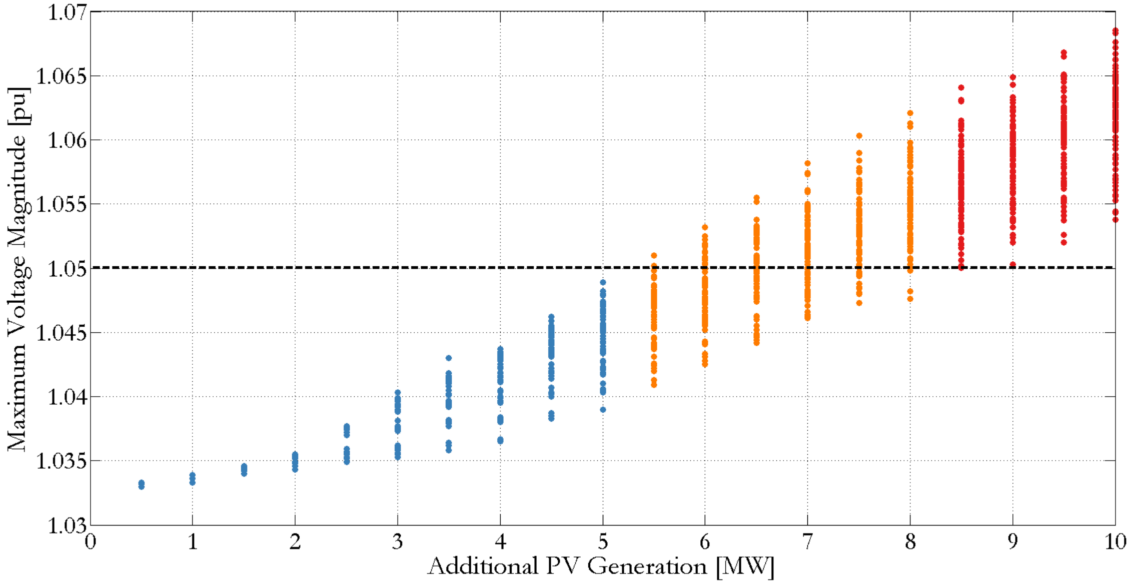


Figure 5-5
Maximum Primary Bus Voltage for Every Large-scale Deployment Case

The change in slope that was discussed in Section 4.3 is still noticeable at 2 MW of additional PV generation, the same amount as for the small-scale. In Figure 5-5 this phenomena manifests itself as the point where the maximum voltage magnitude starts to vary due to the additional PV systems increasing voltage magnitude beyond the value at the substation.

Overvoltage and PV Hosting Capacity

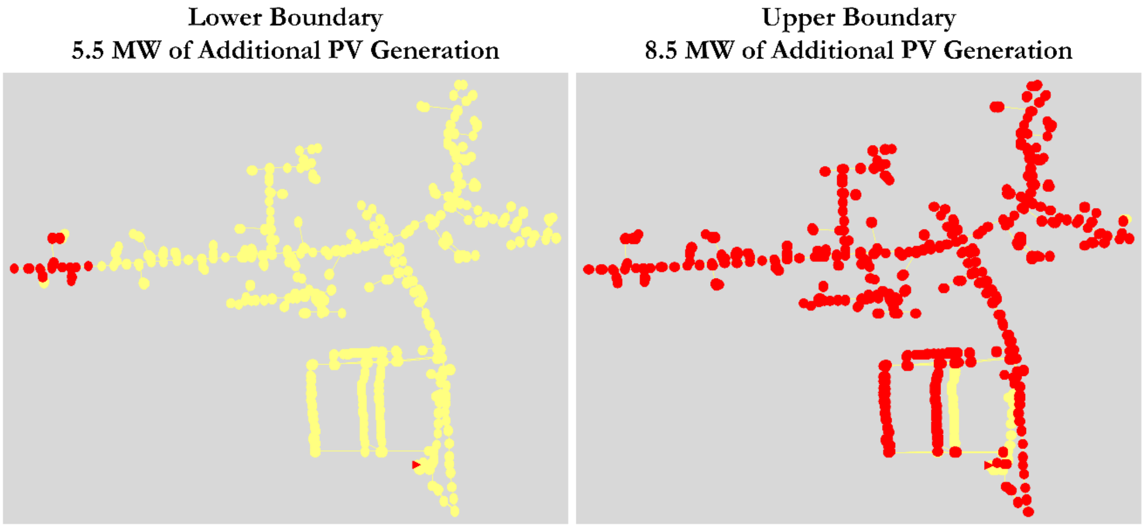
The first overvoltage violation occurs at 5.50 MW of distributed PV generation; this value is defined as the lower boundary of the PV hosting capacity both for this particular case and in regards to voltage rise and hosting capacity. Other deployment scenarios allow more power to be generated by PV systems without causing an overvoltage violation until 8.50 MW have been added, at which point every scenario simulated causes overvoltage at one or more buses.

5.4 OVERVOLTAGE ANALYSIS FOR LARGE-SCALE PV DEPLOYMENT

The PV deployment and the voltage magnitude along the primary wire are depicted in Figure 5-6 for cases at the lower and upper limits of the hosting capacity. The PV deployment figure shows the location and type of PV system, newly added or a previously existing one. The voltage magnitude figure shows where in the system an overvoltage has occurred; a yellow indicator is placed at a bus when the voltage magnitude is less than 1.05 per-unit while a red one is used to indicate overvoltage.

At the lower limit, a cluster of buses at the far end of the circuit experience over-voltage while the rest of the circuit does not. An inspection of the PV deployment in this particular case reveals that 2.50 MW of PV generation, almost half of the total 5.50 MW deployed, is placed in that part of the circuit. Since this scenario represents the lowest estimation of PV hosting capacity, these results indicate that this part of the distribution circuit is the least accommodating of distributed generation.

While the first overvoltage determines the lower boundary and is the most conservative estimation of the PV hosting capacity, the upper boundary is the least conservative estimate, determined by finding the amount of PV generation that causes an overvoltage for all scenarios. For the large-scale deployment, the upper boundary is found at 8.50 MW of additional PV generation. At the upper boundary the overvoltage has spread to most of the primary buses. Still, most of the primary buses that do not exceed the voltage limit are located close to and around the substation, even though a few primary buses in proximity to it have become affected by overvoltage.


Lower Boundary
5.5 MW of Additional PV Generation

Upper Boundary
8.5 MW of Additional PV Generation

Figure 5-6
Voltage Magnitudes at Upper and Lower Boundaries

Maximum Voltage Magnitude Variance

An interesting aspect of the large-scale stochastic simulation results in Figure 5-5 is the disparity between the lowest and the highest maximum voltage magnitude for the same PV generation. This disparity suggests high voltage sensitivity based on different PV deployments scenarios. One of the effects of this sensitivity is a large range of possible PV hosting capacity. The upper boundary is found to be 50% higher than the lower boundary, see Table 5-3. It was mentioned in Section 2.1 that the resistance from the substation to the location of a PV system is inversely proportional to the increase in voltage; the lower the resistance, the lower the resulting rise in voltage due to PV generation. The high variance in the simulation results could therefore be explained if some of the random deployment scenarios deploy many PV systems at the substation while others deploy many PV systems at the far ends of the circuit. This is further explored in Section 5.5.

5.5 LOCATIONAL EFFECTS ON LARGE-SCALE DEPLOYED PV HOSTING CAPACITY

The results of both the small-scale and the large-scale stochastic simulations have indicated that primary buses located close to the substation are less likely to experience overvoltage. The results of the large-scale stochastic model also suggest that a high concentration of PV systems located far away from the substation is more likely to lead to overvoltage. This effect can be examined by deploying PV systems to only a single location and incrementally increasing its output from 0-10 MW, in discrete steps of 0.50 MW. Four locations were selected to explore this effect[4] (see Figure 5-7), one at the substation, one at Mid-feeder and one at one of the ends of the circuit, at Feeder-end 1 and/or at Feeder-end 2. Four PV deployment scenarios are created, one for each of the four locations following the same procedure as described in Sections 5.1 and 5.2.

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[4] The same four locations were also included in the large-scale stochastic simulation in the previous section.

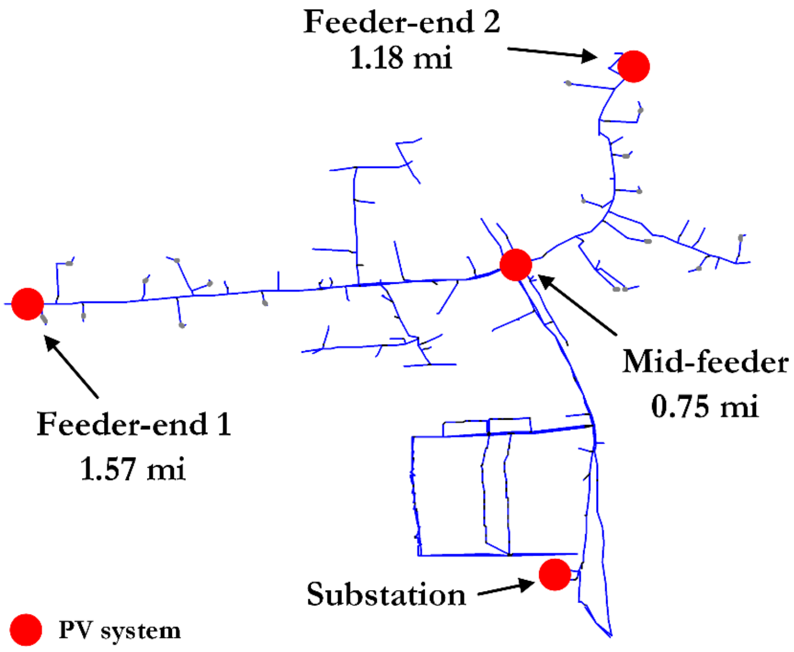

Figure 5-7
Selected Locations for Single Bus PV Deployment

PV Hosting Capacities of the Select Primary Buses

The results, shown in Figure 5-8, reveal an almost linear increase in the maximum voltage magnitude with increasing output of the PV system. The PV hosting capacity of each location can easily be determined by visual inspection. Figure 5-8 shows the maximum voltage magnitude of the circuit as a function of the net PV system output at each of the selected primary buses. The maximum voltage magnitude is least affected when PV systems are deployed at the substation, with no overvoltage violation occurring up-to-and-including the maximum PV generation of 10 MW. The PV hosting capacity for the three remaining locations can be determined by extrapolation from Figure 5-8. Feeder-end 1 has the smallest hosting capacity, accommodating 4.3 MW of PV generation, followed by Feeder-end 2 and Mid-feeder with PV hosting capacities of 4.95 MW and 5.80 MW, respectively.

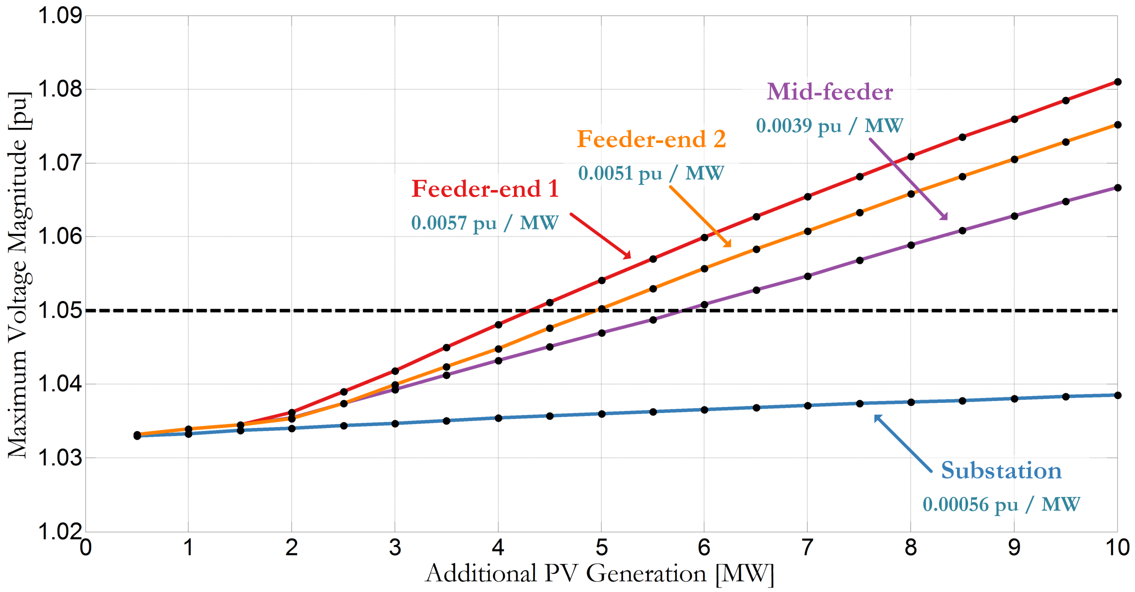

Figure 5-8
Maximum Voltage Magnitude for Single Location, Large-Scale Deployment

Marginal Voltage Magnitude due to PV Generation

An analysis of the results in Figure 5-8 explains the large range in the large-scale, stochastic simulation. The slope of each line describes the sensitivity of the maximum voltage magnitude when the PV generation changes; the higher the slope, the higher the rise in voltage magnitude. The hosting capacity for each bus is found in Table 5-3 along with the distance from the bus to the substation. Discussion in Chapter 2 determined that the PV hosting capacity in a radial distribution circuit is inversely proportional to the distance from the substation. This relationship holds true for the simulation results - the further from the substation a PV system is deployed, the lower the hosting capacity.

PV deployment at the substation results in a very small voltage increase which would explain the variance in the results of the large-scale, stochastic simulation in

Section 5.3. Deployment scenarios that have PV systems deployed to the substation would have little effect on the voltage rise and result in a high PV hosting capacity.

Table 5-2
PV Hosting Capacity of Individual Buses

Location	PV Hosting Capacity [MW]	Distance to Substation [miles]
Substation	>10	0
Mid-feeder	5.80	0.75
Feeder-end 2	4.95	1.18
Feeder-end 1	4.30	1.57

5.6 SUMMARY

The steady-state, stochastic simulation for large-scale PV deployment was implemented to determine the PV hosting capacity of the distribution circuit based on overvoltage. The results of the stochastic simulation showed a large range between the lower boundary and the upper boundary of the PV hosting capacity; see Table 5-3.

Table 5-3
Large-scale PV Hosting Capacity based on Overvoltage

Lower Boundary: **1st Overvoltage Violation**	**5.50 MW**
Upper Boundary: **All Deployments Cause Overvoltage**	**8.50 MW**

Chapter 6
Conclusion

In this work, a steady-state, stochastic simulation method to estimate the PV hosting capacity of given distribution circuit has been further developed and implemented for both small-scale, consumer-level PV deployments and large-scale utility level PV deployments. The simulation method is designed to provide a worst case estimation the distributions circuit's PV hosting capacity, when PV systems are at maximum output levels and the load demand is at a minimum. Due to the stochastic nature of problem, the PV hosting capacity was determined as a range between the most optimum deployment and the least optimum deployment.

For the small-scale PV deployment, a relatively small range was determined. The minimum hosting capacity was estimated as 5.44 MW and the maximum PV hosting capacity as 5.72 MW. The distribution circuit can handle up to 5.44 MW of PV generation regardless of how it is deployed.

For the large-scale PV deployment, the range between the minimum PV hosting capacity and the maximum PV hosting capacity was much greater. The minimum PV hosting capacity was estimated as 4.30 MW, which again, is the most conservative estimate of the PV hosting capacity. The maximum PV hosting capacity as determined by the large-scale stochastic simulation was estimated to be 8.50 MW. A second simulation, where PV systems were deployed to a single location determined that the minimum PV hosting capacity is much larger if all PV systems are deployed to the substation. If all the PV systems would be deployed to the weakest bus at Feeder-end 1, the PV hosting capacity would be lower than 4 MW.

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