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Statistical Analysis of Feeder and Locational PV Hosting Capacity for 216 Feeders

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***Abstract* — As PV penetration on the distribution system increases, there is growing concern about how much PV each feeder can handle. A total of 216 medium-voltage distributions feeders have been analyzed in detail for their individual PV hosting capacity and the locational PV hosting capacity around the feeder. A statistical analysis is performed on the hosting capacity results in order to compare correlation with feeder load, percent of issues caused, and the variation for different feeder voltages. Due to the large number of distribution systems simulated, the analysis provides novel insights into each of these areas. Investigating the locational PV hosting capacity also expands the conventional analytical methods that study only the worst-case PV scenario.**

***Index Terms* -- distributed power generation, photovoltaic systems, power distribution, power system interconnection**

I. Introduction

Large PV installations on the distribution system can have many potential impacts to local customer power quality and reliability, such as high or low voltages, system losses, harmonics, increased wear to regulation equipment, voltage flicker, and system protection. The concept of PV hosting capacity was developed [1-3] in order to study how much PV can be placed on a feeder before negative issues are caused to normal distribution system operation and power quality. 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, 4], and then the results are extrapolated out to similar types of feeders. In this paper, the analysis has been expanded to 216 feeders in order to get a more detailed view of the range and distribution of feeder hosting capacity values. This paper also investigates the use of locational hosting capacity [5] to determine how much PV can be put at different locations of the 216 study feeders. Detailed analysis shows the maximum amount of PV that can be placed through the feeder, and under what conditions various types of violations occur.

II. Distribution Systems Analyzed

A large database of 216 feeders from various utilities throughout the United States [6-11] was simulated using the detailed methodology described in Section III. The feeders range in length from 1.8 km to 52.5 km. The number of buses in each feeder also varies significantly from 142 buses to 6001 buses per feeder. The peak load for each of the feeders ranges from 0.6 MW to 28.5 MW. The number of feeders at each voltage classes is shown in Table I. There is also a range in the incoming high-voltage transmission system at the substation for each feeder from 46 kV to 230 kV.

TABLE I. Feeder Voltage Classes

Voltage Level	4 kV	12 kV	12.47 kV	13.2 kV	13.8 kV	16 kV	19.8 kV	20.78 kV	22.9 kV	24.9 kV	33 kV	34.5 kV
Feeders	18	43	96	3	8	2	16	6	3	9	1	11

For the majority of feeders, the utility also provided at least a year of substation SCADA measurements for the feeder and 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.

Most of the feeders (173 of 216) have no voltage line regulators inside the feeder itself, but as seen in Figure 1, there can be up to 6 regulators per feeder. In total, there are 98 voltage regulators in the database of 216 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.

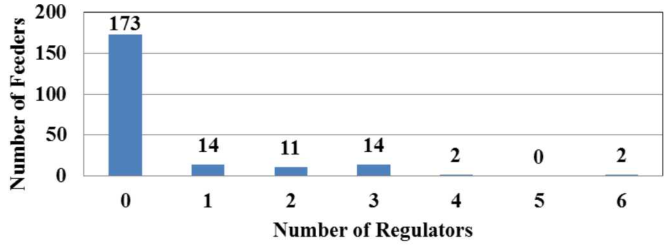

Figure 1. Histogram of the number of voltage regulators on each feeder.

Both the fixed and switching capacitors are modeled for each feeder. As seen in Figure 2, the feeders have between 0 to 13 capacitors per feeder. The highest capacitance on a feeder is a total of 9.9 MVAR total for seven capacitors. 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.

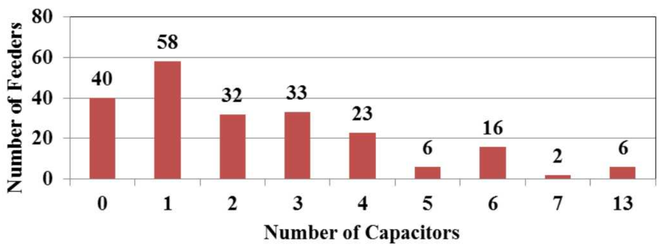

Figure 2. Histogram of the number of capacitors on each feeder.

III. Feeder Hosting Capacity Analysis Methodology

Each of the study feeders is analyzed using a detailed hosting capacity analysis. The methodology in [5, 12] is used to investigate a large number of potential PV scenarios (combinations of PV size and location) in OpenDSS [13]. On average, there are around 40,000 PV scenarios analyzed per feeder. Analyzing such a large number of feeders and interconnections per feeder has resulted in over 3,000 hours of simulation time.

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. Steady-state voltage violations are determined using ANSI C84.1, thermal violations are defined by the component's amp rating, and temporary voltage violations are determined using the ITIC (CBEMA) curve.

Using the detailed simulation results, the PV size is increased at locations around the feeder until an issue or violation occurs on the feeder that impacts the power system quality or operation. The maximum amount of PV that can be placed at a location in the feeder is the locational hosting capacity (LHC). The hosting capacity (HC) of the feeder is the largest amount of PV that can be placed anywhere on the feeder, which is equivalent to the lowest LHC of the feeder.

IV. Hosting Capacity and Locational Hosting Capacity

Throughout the rest of the paper, the PV hosting capacity (HC) and locational hosting capacity (LHC) is analyzed. Each feeder has a single HC value, so there are 216 total HC values. On the other hand, there are many possible interconnection locations on a feeder, so there is a range of LHC values on each feeder. In the 216 feeders, a total of ~60,000 interconnection locations are studied.

A histogram of the HC for the 216 feeders analyzed is shown in Figure 3. The average hosting capacity is 2.05MW, and the median HC is 1.4MW.

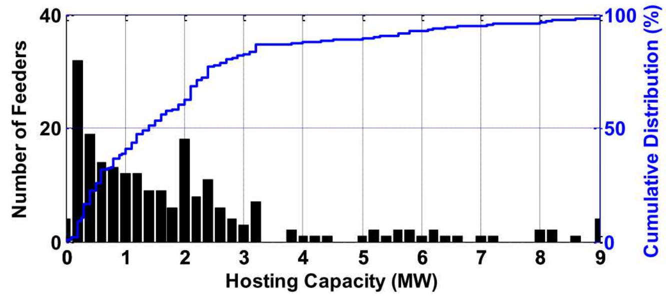

Figure 3. Pareto plot of hosting capacity for all feeders.

Since the HC is the minimum LHC on the feeder, the distribution of LHC goes to larger possible PV sizes on the feeder. For example, the HC of the feeder could be the maximum amount of PV that could be placed at the end of the feeder, while the locational hosting capacity of a potential PV interconnection near the substation could be very large without causing issues. Figure 4 show the histogram of LHC for all 60,000 PV interconnection locations on the 216 feeders. The average locational hosting capacity is 5.1MW, and the median LHC is 3.2MW.

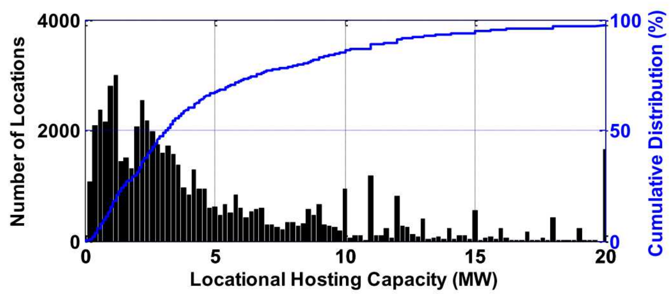

Figure 4. Pareto plot of locational hosting capacity.

V. Hosting Capacity Dependence on Feeder Load

PV hosting capacity analysis is often a snapshot static analysis so that the computations can be achieved in a reasonable timeframe. The methodology in [5, 12] only includes the endpoints (most extreme) of lowest and highest load that have occurred on the feeder during daytime hours of 10am to 2pm. In order to study whether the hosting capacity is limited mostly under the minimum or maximum daytime load, Table I shows the time period that drove both the hosting capacity and locational hosting capacity. From these results, it is most important to study the daytime minimum load period, but daytime peak load periods should also not be ignored because issues caused by PV can first appear under higher levels of load. One interesting finding is that LHC is more often correlated with minimum daytime load than the HC. This can be explained by looking at Figure 8 and Figure 9 where the line loading violations occur mostly at minimum daytime load, and the percentage of LHC violations due to line loading is higher.

TABLE I. THE PERCENT OF FEEDER HOSTING CAPACITIES (HC) AND LOCATIONAL HOSTING CAPACITIES (LHC) THAT FIRST VIOLOATED UNDER DAYTIME MINIMUM OR PEAK LOAD

	HC	LHC
Daytime Minimum Load	80%	89%
Daytime Peak Load	20%	11%

Figure 5 and Figure 6 show histograms of the HC and LHC colored by the load level that issues were first detected. Daytime peak load seems to have more impact on the lower HC and LHC.

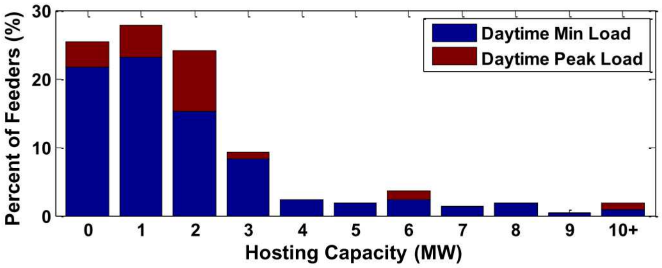

Figure 5. Stacked histogram of feeder hosting capacity colored by the load level that determined the hosting capacity.

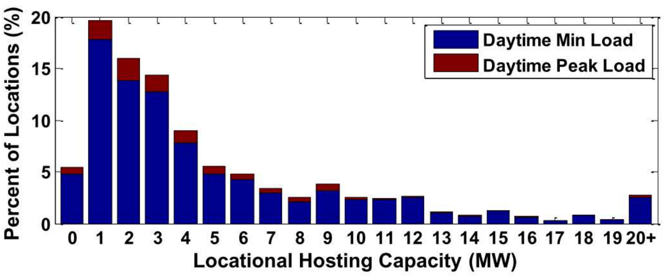

Figure 6. Stacked histogram of locational hosting capacity colored by the load level that determined the hosting capacity of that location.

As seen in Figure 7, the hosting capacity of the feeder is not highly correlated with the feeder's minimum daytime load or 15% of the feeder's peak load. [14] includes more detailed discussion on the correlation between the hosting capacity and 15% of peak load.

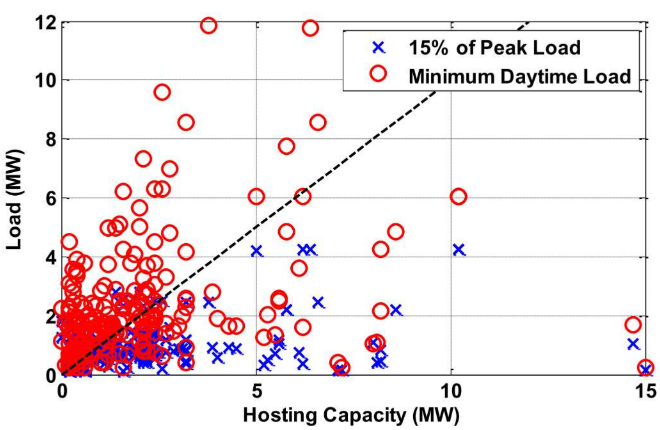

Figure 7. Comparison of hosting capacity vs. 15% of peak load and minimum daytime load. The black dashed line represents the 1:1 correlation line.

VI. HOSTING CAPACITY BY VIOLATION TYPE

Similar to the previous section, the hosting capacity and locational hosting capacity are now compared to the cause for the hosting capacity that more PV could not be installed. The detailed analysis checks for several different types of grid issues that can be caused by PV, each of which can result in a violation that limits the maximum allowable PV size. Table II shows the percentages of HC and LHC that are limited by each type of violation studied. The results here match previous studies like [15] that show most of the feeders and locations are limited by over-voltages caused by the PV.

TABLE II. THE PERCENT OF FEEDER HOSTING CAPACITY (HC) AND LOCATIONAL HOSTING CAPACITIES (LHC) THAT WERE LIMITED BY EACH TYPE OF VIOLATION

	HC	LHC
Over-Voltage	72%	54%
Under-Voltage	2%	3
Line Overload	26%	42%
Transformer Overload	0%	<1%
Multiple Violations	0%	<1%

Figure 8 and Figure 9 graphically show the percentages of HC and LHC that are limited by each type of violation. The percent of locations with LHC limitations caused by distribution system lines being overloaded is much higher than the percent of HC. This is due to the potential PV interconnections closer to the substation or voltage regulators that may stay within normal voltage ranges but violate the thermal ratings of the conductors. Line overloads caused by PV occur when the reverse current on the line is high, so line violations mostly occur under minimum daytime load conditions.

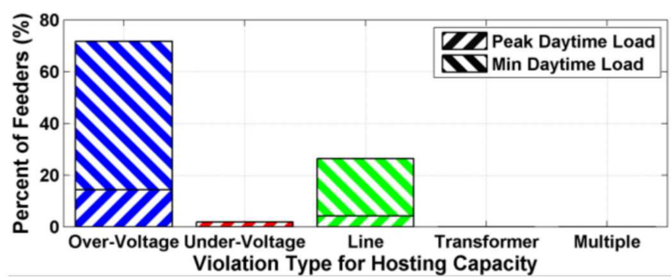

Figure 8. Percent of feeder hosting capacities limited by each violation type.

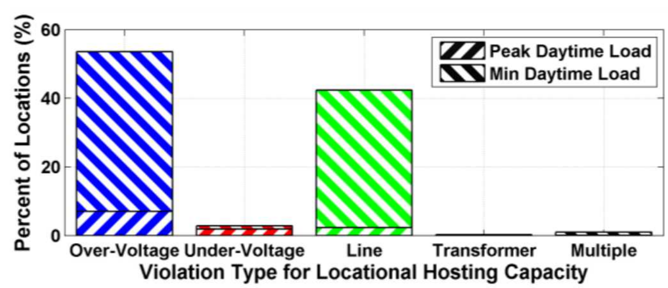

Figure 9. Percent of locations limited by each violation type.

Figure 10 and Figure 11 show the histogram of HC and LHC colored by the type of violation that was first caused by PV. For both HC and LHC, the figures clearly show how over-voltage issues dominate the low hosting capacities, and line loading issues become more common when large PV systems are studied.

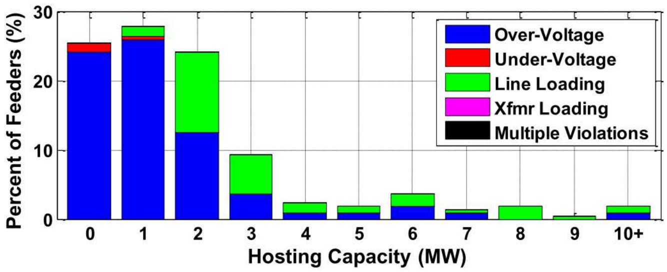

Figure 10. Stacked histogram of feeder hosting capacity colored by the type of violation that deetermined the hosting capacity.

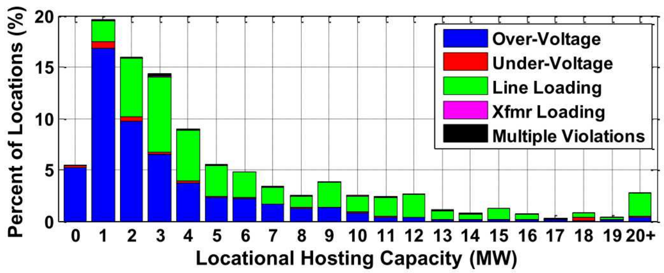

Figure 11. Stacked histogram of locational hosting capacity colored by the type of violation that determined the hosting capacity of that location.

VII. Hosting Capacity by Voltage Level

The grid impacts caused by PV are highly dependent on the voltage level of the feeder. The lower voltage classes result in more current injection for the same PV size, which causes more losses, more voltage change, and more thermal overloads. The results from the 216 feeders have been separated into four voltage classes, as shown in Figure 12. The CDF of feeder hosting capacities demonstrates how differently each voltage classes responds. For example, the 4kV feeders generally have a HC less than 1MW, but none of the 34kV feeders have a HC less than 1MW.

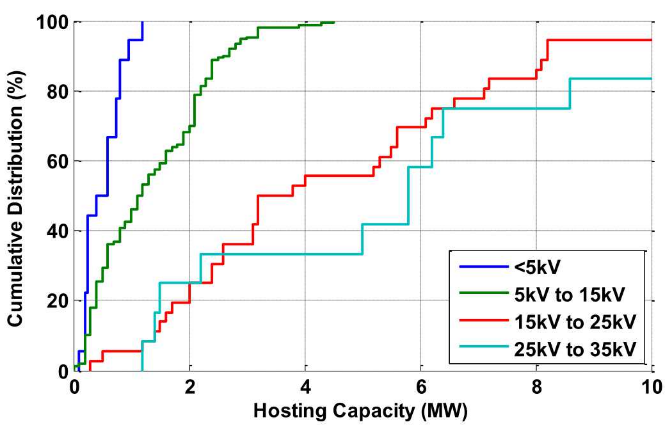

Figure 12. CDF of feeder hosting capacity separated by voltage class.

The results for LHC grouped by feeder voltage class demonstrate similar results in Figure 13. In fact, since the HC is the minimum LHC, the initial increase (intersection with the x-axis) is the same in both figures. However, the cumulative distribution function (CDF) of the LHC is significantly higher for the other buses on each feeder.

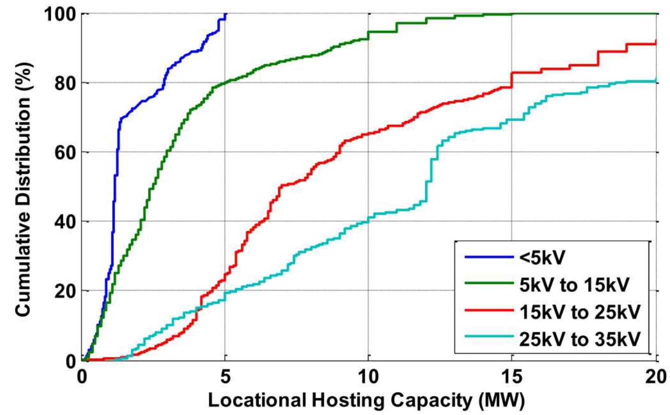

Figure 13. CDF of locational hosting capacity separated by voltage class.

The distribution of HC and LHC can also be visualized using a box and whisker plots shown in Figure 14 and Figure 15. The red line shows the median, and the blue box shows the middle quartiles (from the 25th to 75th percentile). For both the HC and LHC, the median voltage increases with the voltage level of the feeder. For each voltage level, the median LHC is approximate twice the median HC.

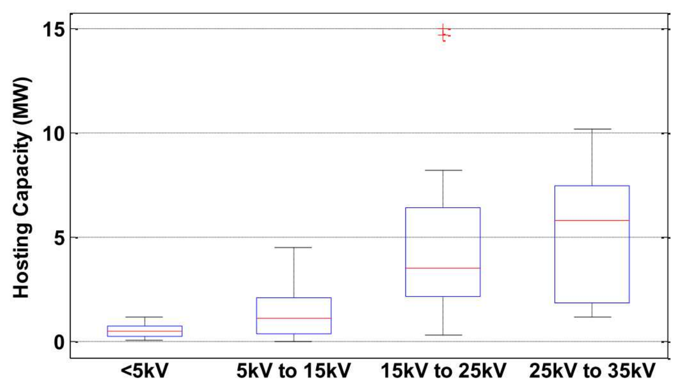

Figure 14. Box plot of feeder hosting capacity separated by voltage class.

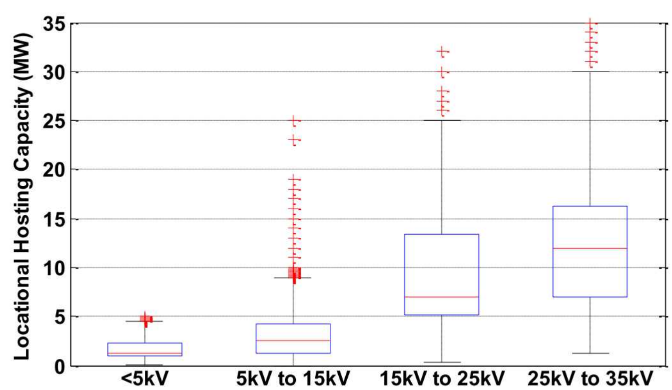

Figure 15. Box plot of locational hosting capacity separated by voltage class.

VIII. Correlation between Voltage Level and Violation Type

Using the methodology in [12], the PV interconnection risk is visualized for each interconnection, instead of only the first problem caused on the feeder. For example, if an over-voltage violation was mitigated using a technique like [16] to increase the PV hosting capacity, the question is how much higher of a PV penetration can be placed on the feeder. For any given PV size, the number of PV scenarios that results in each type of violation is known, even if it is above the HC or LHC. Due to the differences in voltage classes noted in the previous section, the analysis is separated by voltage class. The two most common voltage classes (12kV and 20kV) are shown in Figure 16 and Figure 17. This shows an aggregate figure of all locations on all feeders inside the voltage class. The black lines in Figure 16 and Figure 17 match the corresponding lines for their voltage class in Figure 13. By separating out the type of violations, new insights can be found, such as under that voltage issues can arise more than 15% of the time on 12kV feeder with 10MW PV systems even though this violation is not often the first issue to be caused. There is also a clear trend on the 12kV feeders where many of the conductors are rated in the 2-4 MW range (100 – 200 amps). On the other hand, the 20kV voltage class feeders have a much wider range of conductor ratings with the green line slowing increasing from 4MW to 12MW in Figure 17.

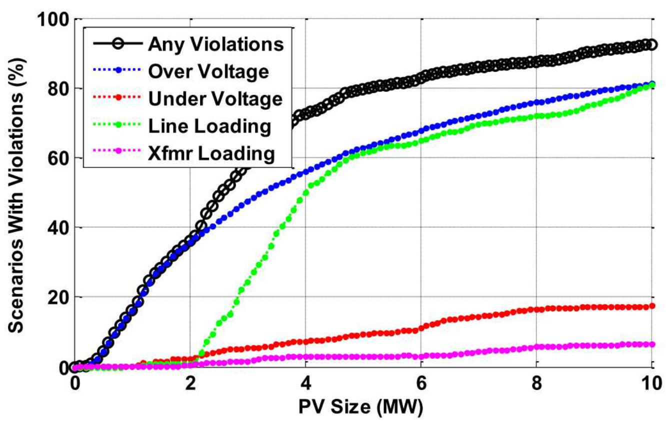

Figure 16. PV scenarios on all 5kV to 15kV feeders that have violations.

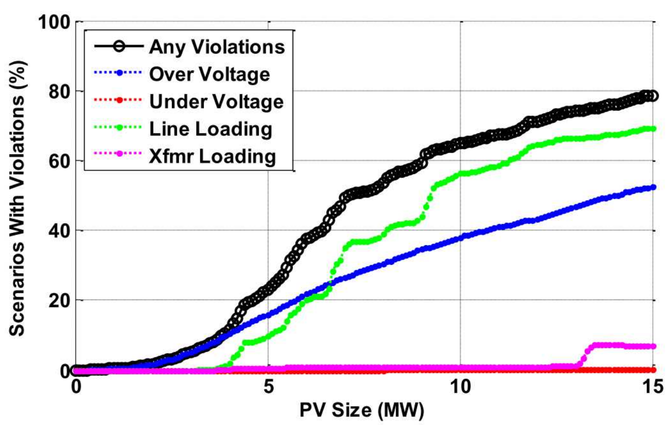

Figure 17. PV scenarios on all 15kV to 25kV feeders that have violations.

IX. Conclusions

A large database of 216 medium-voltage distributions feeders have been analyzed in detail for their PV hosting capacity. The locational hosting capacities for locations around each feeder are also studied for around 60,000 potential PV interconnection locations. A statistical analysis was performed on the hosting capacity results in order to compare correlations with feeder load, percent of issues caused, and the variation for different feeder voltages. The PV hosting capacity of most feeders is limited by over-voltages caused by PV, but line loading thermal limitations often become the violation that determines the locational hosting capacity. Both HC and LHC are largely limited under low load conditions on the feeder, such as minimum daytime load, but occasionally the first issue caused by PV can occur at peak daytime load. Finally, the HC and LHC are highly dependent on the voltage level of the feeder, and the types of issues caused by PV also change depending on the voltage class.

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