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Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders

Anderson Hoke, Rebecca Butler, Joshua Hambrick, and Benjamin Kroposki

Abstract

This paper presents simulation results for a taxonomy of typical distribution feeders with various levels of photovoltaic (PV) penetration. For each of the 16 feeders simulated, the maximum PV penetration that did not result in steady-state voltage or current violation is presented for several PV location scenarios: clustered near the feeder source, clustered near the midpoint of the feeder, clustered near the end of the feeder, randomly located, and evenly distributed. In addition, the maximum level of PV is presented for single, large PV systems at each location. Maximum PV penetration was determined by requiring that feeder voltages stay within ANSI Range A and that feeder currents stay within the ranges determined by overcurrent protection devices. Simulations were run in GridLAB-D using hourly time steps over a year with randomized load profiles based on utility data and typical meteorological year weather data. For 86% of the cases simulated, maximum PV penetration was at least 30% of peak load.

Keywords

Distributed power generation, photovoltaic systems, power distribution, power system simulation

I. Introduction

As the portion of electrical energy produced by distributed resources increases, concerns heighten over the potential for such resources to create steady-state voltage or current violations on electrical distribution feeders [1]-[3]. When power generated from distributed resources exceeds the load on a feeder or section of a feeder, voltages may rise on that section. In addition, significant aggregations of distributed resources may cause feeder currents to approach or exceed design currents. This study simulates various levels of photovoltaic (PV) penetration on several typical distribution feeders at a variety of locations on the feeders, in order to determine which levels of penetration create voltage or current problems. This work considers only steady-state voltage and current. It does not consider generation ramp rates, protection and coordination, or other issues that might impact maximum feeder PV penetration. Some of the maximum PV penetration results presented here are very high and are best interpreted as indicating that steady-state voltage and current do not limit PV penetration in the relevant cases, not that very high PV penetrations are necessarily achievable.

A commonly used rule of thumb in the U.S. allows distributed PV systems with peak powers up to 15% of the peak load on a feeder (or section thereof) to be permitted without a detailed impact study [4]. This necessarily conservative rule has been a useful way to allow many distributed PV systems to be installed without costly and time-consuming distribution system impact studies. However, as total distributed PV power increases on many feeders, and as PV systems whose peak power is a significant fraction of feeder capacity become more common, a more rigorous study of the impacts of various PV penetration levels on feeder voltages and currents is justified.

To model the effects of various PV penetrations across the wide spectrum of U.S. distribution feeder architectures, this study employs a publicly available taxonomy of 24 radial distribution feeder models developed at Pacific Northwest National Laboratory (PNNL) [5]. The 24 models represent detailed utility feeder models, which statistically represent typical radial distribution feeders from five U.S. climate regions. The models are based on 575 utility feeder models gathered from 17 utilities including public, municipal, and investor-owned utilities, as well as Rural Electrification Association members. The taxonomy feeders do not contain geospatial information, as a condition of the agreement under which the utilities provided the models. The simulation platform used to model the feeders is PNNL's GridLAB-D version 2.2 [6]. Due to software limitations, eight of the 24 feeders were not used in this study.

For this study, each of the load points in the 16 taxonomy feeders was populated with hourly averaged load data from a utility in the feeder's geographical region [5], scaled and randomized to emulate real load profiles. Photovoltaic systems driven by typical meteorological year (TMY2) weather data were then inserted in each feeder model according to each of the location scenarios described in Section II. For each combination of feeder and PV location scenario, annual simulations were performed at PV penetration levels of 15% of peak load, 30% of peak load, 45% of peak load, etc. Maximum and minimum feeder voltages were recorded for each simulation, and simulations were continued at increasing PV levels until voltage exceeded ANSI Range A or current exceeded the overcurrent protection rating at some point in the circuit. In this manner, maximum PV penetrations were determined for each feeder under each PV location scenario. This process is described in detail in Section II, and results are presented in Sections III and IV.

II. Methodology

In this study, *PV penetration* is defined as the ratio of total peak PV power to peak load apparent power on the feeder:

$$\text{PV Penetration} = (\text{Peak PV Power}) / (\text{Peak Load Apparent Power})$$

A. Feeder Loading

The taxonomy feeders used for this study do not incorporate time-varying load information. Annual load profiles (8760 hourly loads) were developed for each load location using three steps:

1. An appropriate averaged load profile for each load class (commercial and residential) was obtained from a utility in the feeder's geographical region, as defined in [5]. For region 5, comprising the far Southeast near the Gulf of Mexico, no load profile information was publicly available, so load profile data from region 4 was used. Commercial loads were assigned a load profile from the utility's medium- or large-sized commercial/industrial load class, and residential loads were assigned a load profile from the residential load class.
2. The load profiles were then scaled according to a feeder-specific scale factor, *sf*, and the transformer capacity at each load point. In this study, *sf* is defined as the ratio of peak apparent load power to total rated load transformer apparent power. For each feeder, *sf* was determined by running multiple yearly simulations with one-hour time steps, varying *sf*. A bisection search was used to find the maximum *sf* for each feeder that maintained load voltages within ANSI

Range A, line currents below their respective continuous current ratings, and fuse currents below fuse ratings. Fig. 1 shows the maximum scaled load found by simulation for each feeder alongside its nominal load given in [5]. Fig. 2 shows an analysis of the correlation between maximum scaled feeder loads as found by simulation and nominal feeder loads. While overall correlation between simulated maximum load and nominal load is relatively strong, certain individual feeder peak loads diverge significantly from nominal loads because the same loading algorithm was applied to all feeders. This has a significant impact on PV penetration results and contributes to some anomalous results discussed later; for example, feeder R1-12.47-3 has relatively low load so its maximum PV penetration as calculated from (1) is skewed high.

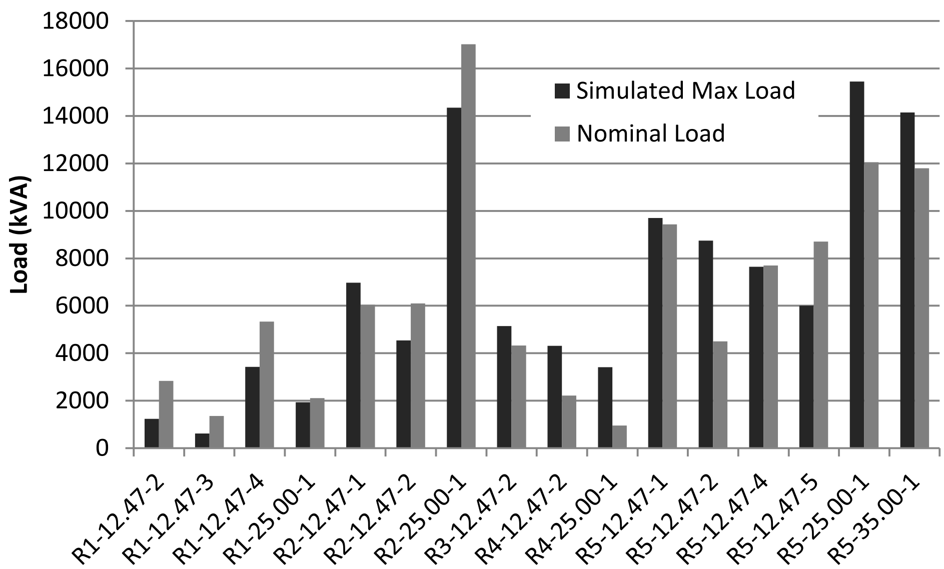


Fig. 1. Maximum feeder loads found by simulation vs. nominal feeder loads.

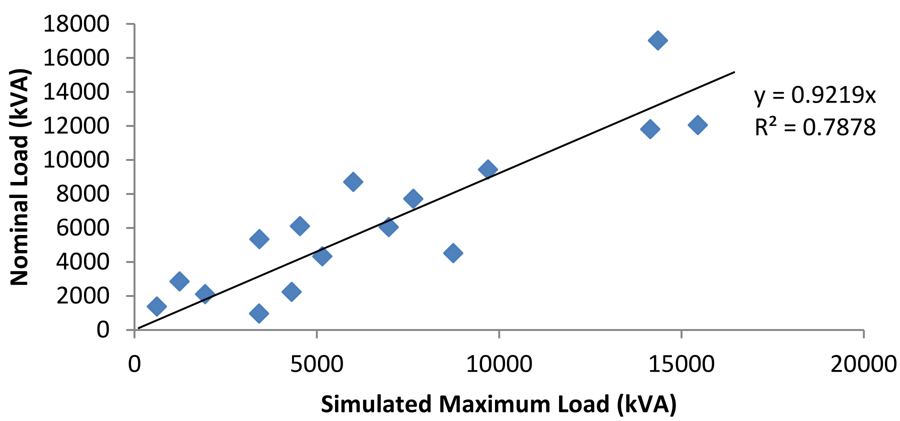


Fig. 2. A linear fit of nominal load to maximum feeder load found by simulation.

3. To reflect the stochastic nature of real loads, the load profiles were then randomized. Each of the 8760 scaled annual load values for each load point was multiplied by a factor sampled from a Gaussian (normal) distribution. The standard deviation of the Gaussian distribution was 0.2, and its mean value was 1.0. This resulted in a load diversity factor of about 1.3 for each load class. Each transformer feeds exactly one load, indicating that the creators of the feeders may

have consolidated the feeder loads. To account for this consolidation a nominal residential load size of 5 kVA was assumed, and randomization was applied to each 5-kVA increment for residential transformers. No typical load size was assumed for commercial transformers because commercial loads vary widely in size. Hence the amplitude of random hour-to-hour fluctuations in commercial loads is much larger than for residential loads, and also larger than it would be in a typical feeder. Some of the random variations in load profiles disappear when they are aggregated into a total feeder load profile. Randomizing loads after application of the scaling factor caused some minimum annual load voltages to drop below ANSI Range A, but remain within ANSI Range B, which reflects the conditions on physical feeders. Occasionally, randomization of loads caused overcurrents in the baseline (no PV) year-long simulation. In those cases, all loads on the feeder were reduced by 25% and the base case was re-simulated. Finally, a power factor of 0.9 was applied to all loads. Fig. 3 shows final scaled and randomized total load profiles (residential and commercial) for one feeder over two days, compared to the reference load profiles for the feeder's region.

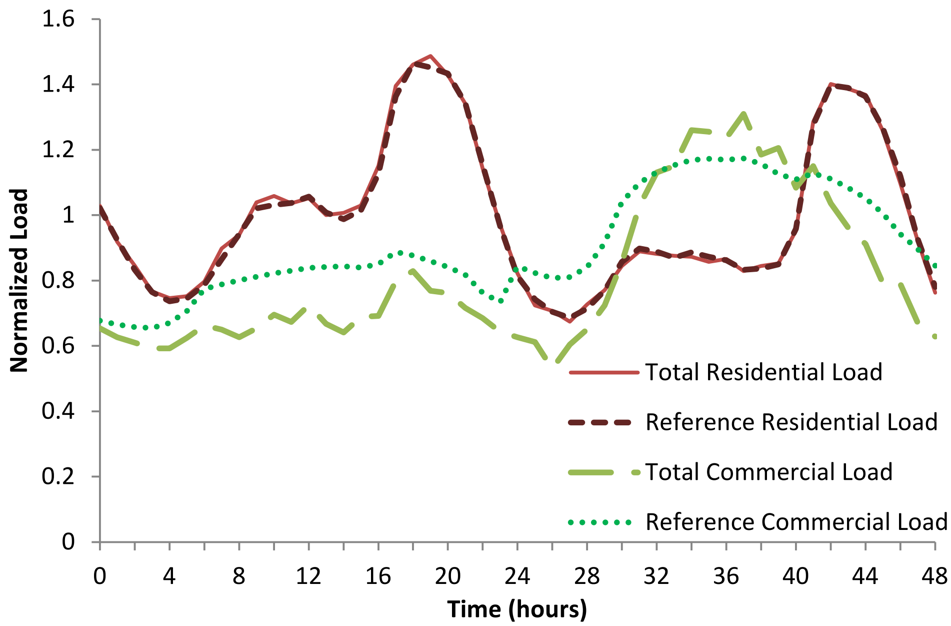


Fig. 3. Total normalized residential and commercial loads for feeder R1-12.47-4 over two days (one weekend and one weekday), plotted with the normalized residential and commercial reference load profiles for region 1. The total residential load follows its reference profile much more closely than the commercial load profile because this feeder has more residential transformers, and because the residential transformers are randomized in 5-kVA increments. With just 12 commercial transformers on this feeder, the largest transformers dominate the total load, so random variations applied to those loads lead to significant deviations from the reference load profile.

B. PV location scenarios

After applying appropriately scaled and randomized load profiles, each feeder was simulated at various PV penetrations under several PV location scenarios. The scenarios studied include five distributed PV scenarios and four scenarios with one PV system per feeder. The methodologies used to produce these nine PV location scenarios are as follows:

Distributed PV: The first five location scenarios all involve several distributed PV systems on the same feeder. In these scenarios, each PV system is installed at the location of an existing load and is scaled according to the load size and the desired PV penetration level. The distributed PV scenarios are:

1. PV clustered near the substation source
2. PV clustered near the midpoint of the feeder
3. PV clustered near the end of the feeder
4. PV evenly distributed throughout the feeder
5. PV randomly distributed throughout the feeder

To produce scenarios 1, 2, and 3, the existing load points on a feeder were sorted according to distance from the feeder source, where *distance* is defined as total conductor length from the source to the load in question. A PV system was added at the load point that best fits the desired location criterion, sized with peak PV power at 80% of the load's transformer rating. Another PV system was then added at the next-best-fitting load point, sized in the same way. This process continued until the desired PV penetration was reached. For example, to produce scenario 2 (PV near the midpoint), the load closest to the middle of the feeder received PV first, then the load second-nearest to the middle of the feeder received PV, and so on, until the desired PV penetration was reached. For PV penetrations exceeding 70%, the PV systems added to each load point were sized at 1.5 times the desired PV penetration multiplied by *sf*, multiplied by the respective load transformer rating.

To produce scenario 4, PV was added at all load points. The peak PV power was set equal to the desired PV penetration, multiplied by *sf,* multiplied by the applicable load transformer rating. As a result, each load point has a PV system sized in proportion to its transformer size to achieve the desired PV penetration.

To produce scenario 5, the various load points were sorted into a random order and PV was added to successive load points until the desired PV penetration was reached.

In all of scenarios 1, 2, 3, and 5, the size of the final PV system added was scaled down to achieve the desired PV penetration exactly.

Note that clustering PV near the end of a feeder does not necessarily result in PV systems that are physically or electrically close together. For example, in scenario 3, a feeder with two branches of approximately equal length would receive some PV near the end of each branch.

Single PV system: The remaining four location scenarios all involve a single, large PV system on a feeder. In these scenarios, the PV system was not installed at the location of an existing load, but rather was installed on its own transformer that was added specifically for the PV system. This transformer is not included in the total load transformer power. The single PV system scenarios are:

6. Single PV system close to the feeder source

7. Single PV system near the feeder midpoint
8. Single PV system at the end of the feeder
9. Single PV system at a randomly selected point

To site the single PV system in scenarios 6, 7, and 8, all three-phase nodes on the circuit were sorted by distance from the feeder source and the PV system and its transformer were installed at the location that best fits the desired scenario. For example, to produce scenario 8, a single PV system and transformer were installed at the farthest three-phase node from the source. For scenario 6, the node where the PV system was installed was required to be at least 300 feet from the source to ensure that the system was downstream from the feeder substation components.

To produce scenario 9, the PV system and transformer were placed at a randomly selected three-phase node, again with the requirement that the node be at least 300 feet from the feeder source.

For each of these scenarios, the PV system was sized so that it alone would meet the PV penetration goal. The transformer was sized to have a rated apparent power 20% larger than the PV system peak rated power. During simulation of scenarios 6-9, current was monitored in the line immediately upstream from the PV system and compared to the continuous summer current rating of the line. Voltage was monitored at the PV system point of common coupling (and as in all scenarios, the voltage at all loads and the status of all fuses were monitored).

All PV systems simulated were installed at locations chosen by a computer algorithm that—to avoid introducing bias—did not evaluate the locations' suitability for PV. For the distributed PV cases all load points were considered, and for the single PV system simulations all three-phase nodes were considered.

C. PV penetration levels

For each of the nine scenarios and 16 feeders, GridLAB-D simulations were performed at PV penetrations of 0% (the base case), 15%, 30%, and so on, with 15% steps until an overvoltage or overcurrent was detected at any point during the year. In cases where the PV penetration reached higher than 100% of peak load, the step size was increased to 50%. A bisection search was then conducted to define the maximum PV penetration more narrowly. The resolution of the bisection search for PV penetrations below 150% was 5 percentage points. Above 150% penetration, the resolution began rising based on the assumption that, for these very high penetration cases, the exact maximum penetration is not as relevant as the insight that maximum PV penetration is not limited by steady-state voltage or current. The maximum search resolution was 30 percentage points.

III. Distributed PV Results and Analysis

This section describes simulation results for the distributed PV location scenarios (scenarios 1-5). Scenarios 1 through 4 were simulated once for each feeder, and the random location scenario was simulated five times for each feeder.

Table 1 lists the maximum PV penetration results for the various distributed PV scenarios. The number preceded by "R" in each feeder name indicates its geographical region. Values of maximum PV penetration obtained vary widely among the feeders, reflecting the diversity of physical feeder configurations. Maximum PV penetration also varies widely from one location to another on most feeders. All feeders tolerate at least 75% PV penetration in at least one case.

Table 1: Maximum PV Penetration for All Distributed PV Scenarios

Location / Feeder	Near Source	Mid-feeder	End of Feeder	Evenly Distributed	Random					Minimum	Maximum
R1-12.47-2	255	45	30	230	111	155	193	149	56	30	255
R1-12.47-3	243	230	218	255	255	255	255	255	255	218	255
R1-12.47-4	155	155	155	230	155	168	155	155	155	155	230
R1-25.00-1	380	255	130	280	205	230	243	255	280	130	380
R2-12.47-1	105	155	180	205	155	155	155	155	155	105	205
R2-12.47-2	205	205	168	218	168	205	168	180	168	168	218
R2-25.00-1	0	26	26	101	8	8	8	4	4	0	101
R3-12.47-2	155	155	205	180	180	180	168	168	155	155	205
R4-12.47-2	155	155	155	205	205	155	155	280	155	155	280
R4-25.00-1	155	155	105	205	155	180	155	155	155	105	205
R5-12.47-1	205	168	155	230	180	205	168	243	168	155	243
R5-12.47-2	94	90	83	105	90	98	94	98	94	83	105
R5-12.47-4	4	11	8	86	8	8	4	19	19	4	86
R5-12.47-5	8	4	34	86	15	15	4	45	30	4	86
R5-25.00-1	56	45	11	75	64	19	23	26	41	11	75
R5-35.00-1	8	0	0	75	0	11	15	0	0	0	75

Maximum PV penetration for many feeder-location combinations reaches well over 100%. For these very large PV penetrations, it is likely that other effects not modeled in this study would limit physical PV penetration levels. For example, the taxonomy feeders do not include models of the substation transformer connecting the distribution feeder to the transmission system. This transformer's power rating would likely become a limiting factor in cases of very large PV penetration. Also, the transmission system is represented as an ideal voltage source in GridLAB-D, so any voltage rise it may experience due to very high PV penetrations is neglected. Similarly, dynamic concerns such as generator ramp rates are neglected. Other factors that are not addressed in this study and may limit PV penetration at moderate penetrations include protection, coordination, and power quality issues [7], [8]. Therefore, in very high penetration cases, it is more appropriate to conclude that steady-state voltage and current are not the limiting factors than that the feeder can actually tolerate such high levels of PV.

While in general maximum PV penetration results were quite high, several feeders, especially those in region 5, show relatively low limits to PV penetration. In general these feeders exhibited very high hourly average and maximum load voltages even when simulated without PV. The five feeders with the lowest limits to PV penetration (feeders R2-25.00-1, R5-12.47-4, R5-12.47-5, R5-25.00-1 and R5-35.00-1) all have maximum baseline (no PV) load voltages above 1.037 pu. The possibility that maximum baseline load voltages are high due to under-loading of these feeders by the loading methodology has been eliminated by examining minimum baseline hourly-average load voltages, which range from 0.96 to 0.99 pu on these five feeders. Fig. 4 examines the relationship between maximum baseline feeder load voltage and maximum PV penetration. The data in Fig. 4 suggest that while a high baseline voltage does not guarantee a low limit to PV penetration, a low limit is more likely.

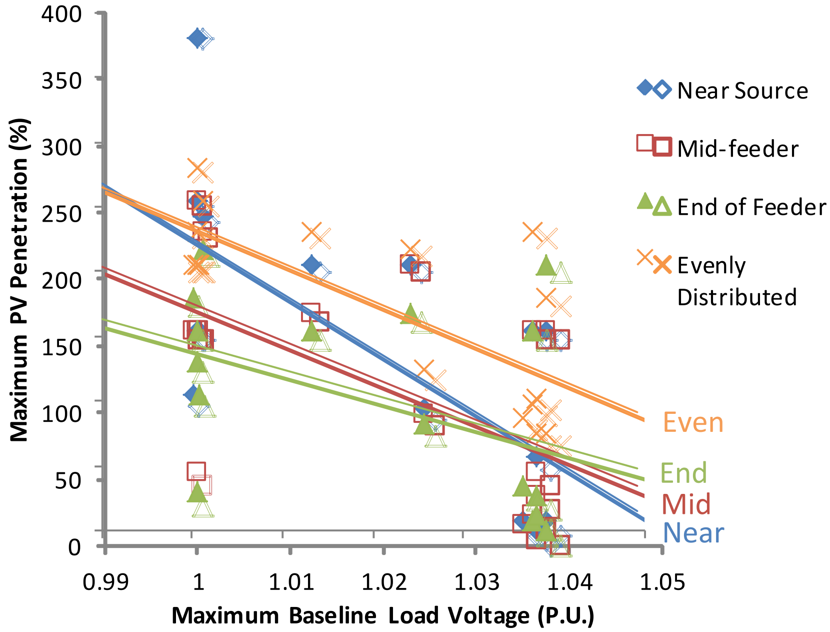


Fig. 4. Maximum distributed PV penetration versus maximum baseline load voltage with linear fits shown for each location scenario.

Fig. 5 shows maximum PV penetration results by feeder for the non-random location scenarios. PV penetration limits are above 50% except for a few outliers. Most of the outliers correspond to the previously-identified five feeders where maximum and average baseline load voltages are relatively high. In addition to these feeders, two cases of maximum PV penetration below 50% remain: PV at mid-feeder and end-of-feeder on R1-12.47-2. Notably, these are the same two outlier cases that appear in the lower left corner of Fig. 4. Both cases are limited by overcurrent conditions.

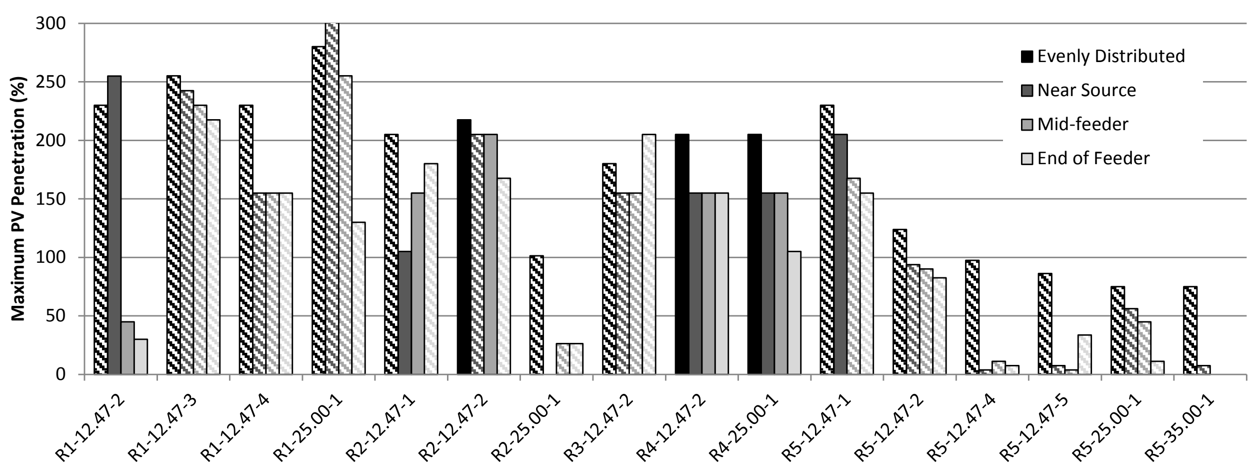


Fig. 5. Maximum PV penetration for all non-random, distributed location scenarios. Solid columns indicate PV penetration was limited by overcurrent; otherwise PV penetration was limited by overvoltage. One result over 300% has been truncated.

For the feeders that exhibit low PV tolerance, all are most tolerant of evenly distributed PV. In fact, maximum penetration for evenly distributed PV is at least 75% in all cases. However, encouraging or enforcing the even distribution of PV on a feeder would likely be difficult in practice.

The five simulations involving randomly located distributed PV on feeder R1-12.47-2 all resulted in maximum penetrations above 50%, and four of the five were above 100%. In addition, the feeder's limit for single large PV systems was above 100% in all scenarios, indicating that the feeder does tolerate large amounts of distributed PV in most scenarios. The two cases of low maximum PV penetration on feeder R1-12.47-2 are due to overcurrent and appear to result from weak spots on smaller branches of the distribution feeder. For the mid-feeder case, voltage was not a problem until PV penetration was over 100%. For the end-of-feeder case, overvoltages occurred for PV penetrations above 34%, indicating that this feeder has a low tolerance for PV located far from the source from both voltage and current perspectives.

Because switched capacitors can influence feeder voltages significantly, the relationship between maximum PV penetration and the presence of switched capacitors performing voltage control was also examined. No notable correlation was found.

IV. Single PV System Results and Analysis

This section describes simulation results for the PV location scenarios involving a single PV system per feeder (scenarios 6-9). Each of scenarios 6-8 was simulated once for each feeder, and the random location scenario was simulated nine times for each feeder.

Table II lists the maximum PV penetration results for all feeders and all single PV system scenarios simulated. The maximum penetrations in Table II tend to be higher than those found for the distributed PV scenarios. In several cases the maximum penetration was over 500% of peak load, which, for the reasons listed in Section III, is a much larger PV system than would be considered for installation.

Table 2: Maximum PV Penetrations for all Single-System Scenarios

Location / Feeder	Near Source	Mid-feeder	End of Feeder	Random									Min.	Max.
R1-12.47-2	155	255	270	255	755	255	255	255	255	755	530	755	155	755
R1-12.47-3	1683	655	708	1455	1455	780	655	705	655	880	1505	705	655	1683
R1-12.47-4	436	230	45	193	45	205	405	30	255	430	355	330	30	436
R1-25.00-1	955	280	139	580	280	405	680	1005	149	1005	955	630	139	1005
R2-12.47-1	230	45	56	94	79	56	30	180	15	41	15	56	15	230
R2-12.47-2	330	218	75	60	380	430	60	45	15	218	380	355	15	430
R2-25.00-1	255	180	94	56	205	155	180	60	205	230	155	105	56	255
R3-12.47-2	111	205	30	205	79	15	405	45	56	118	15	30	15	405
R4-12.47-2	355	105	430	330	255	30	90	45	330	155	355	180	30	430
R4-25.00-1	805	805	805	805	805	805	805	805	805	805	805	805	805	805
R5-12.47-1	280	305	45	75	305	15	255	30	305	60	255	193	15	305
R5-12.47-2	243	15	60	45	68	60	15	243	15	75	243	68	15	243
R5-12.47-4	330	130	60	86	49	45	155	118	111	45	38	26	26	330
R5-12.47-5	280	30	90	15	64	45	45	230	30	60	30	305	15	305
R5-25.00-1	168	124	94	83	45	180	15	136	136	71	180	15	15	180
R5-35.00-1	330	30	45	79	230	75	255	280	305	330	330	218	30	330

The highest maximum penetration result was 1680% for the case of a single large PV system near the source of feeder R1-12.47-3. Feeder R1-12.47-3 was a lightly loaded feeder, so quantifying PV penetration relative to load (rather than some measure of feeder capacity) is partly responsible for the very high penetration value. The peak load of this feeder is 34% of total load transformer rating, so 1680% of peak load represents 570% of the feeder's total load transformer rating, which is still a very high penetration. As mentioned in Section II, the single PV system installed in PV location scenarios 6-9 is installed on its own new transformer (and this transformer's power rating is not included in the total load transformer rating). The rated peak DC power of the PV system is 9.2 MW, and the maximum measured AC output power of the PV system was 7.5 MW. The maximum measured currents on the three phases of the line immediately upstream from the PV system were 334, 325, and 333 A, which are just within the per-phase continuous summer current rating of the line, 334 A. The peak backflow power was approximately 7.1 MW. The rest of the feeder was therefore drawing 7.5-7.1 = 0.4 MW at the time of peak backfeed power. The nominal peak feeder load is 1.4 MW, and the simulated peak feeder load was 0.56 MW. The power going back into the substation is about 7.1 MW, or 5.1 times the nominal peak load. Therefore this feeder's maximum PV penetration for an installation located very near the source would very likely be limited by substation equipment power and protection settings to a much lower value than that found here. The PV system was installed 472 feet from the feeder source, and the maximum voltage on the PV side of the transformer was 1.003 pu – reasonable given that very little voltage rise is expected over such a short distance.

Feeder R4-25.00-1 showed the same very high maximum PV penetration of 805% for all single PV system scenarios. The three-phase section of this feeder (which is the only section where our algorithm installed PV in scenarios 6-9) extends only about 1.2 miles and consists of a single line with one short branch. This line and its branch have the same continuous summer current rating of 530 A per phase over their entire lengths, and that current rating was the limiting factor in all single PV system scenarios, leading to identical penetration limits in all cases. As in other very high penetration cases, unmodeled factors would limit PV penetrations to lower values than those found in this study.

The range of maximum PV penetration results for each single PV system scenario tends to be wider than the range for distributed PV systems. The difference in ranges is more than expected based solely on the higher number of simulations performed. The wider range of PV tolerances reflects the variation in PV tolerance from one node to another in the feeder; a node that happens to be on the main feeder line is likely to have a much higher PV tolerance than a node on a small branch line. In contrast, a distributed group of PV systems becomes too large when any of the many affected points on the feeder experiences overvoltage or overcurrent; the variation from one group to another is smaller due to aggregation effects.

Compared to the distributed PV scenarios, more feeders showed *minimum* PV tolerances of less than 30%. This is expected; putting a single PV system sized at more than 30% of the entire feeder's peak load on a small branch will cause voltage and/or current problems.

The relationship of maximum PV penetration to maximum baseline meter voltage was analyzed (Fig. 6). Again, the trend is for PV tolerance to decrease with increasing voltage, although there are more outliers than in Fig. 4, reflecting the high case-to-case variation in single PV system scenarios.

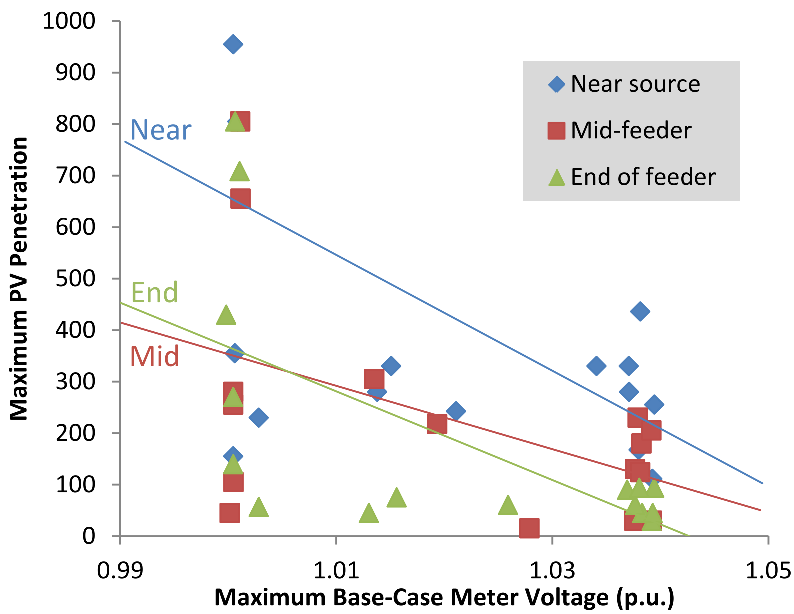


Fig. 6. Maximum single-system PV penetrations as a function of maximum baseline load voltage, with linear fits shown for each location scenario.

Simulations with single PV systems provide an opportunity to examine the relationship between maximum PV penetration and distance from the PV system to the feeder source. This relationship is shown in Fig. 7, where distance was measured by following the conductors back to the source. This shows a definite trend of decreasing PV tolerance with distance. There are, however, many exceptions to the trend. These exceptions are largely because some PV systems were installed on smaller feeder branches by the intentionally unintelligent PV location algorithm.

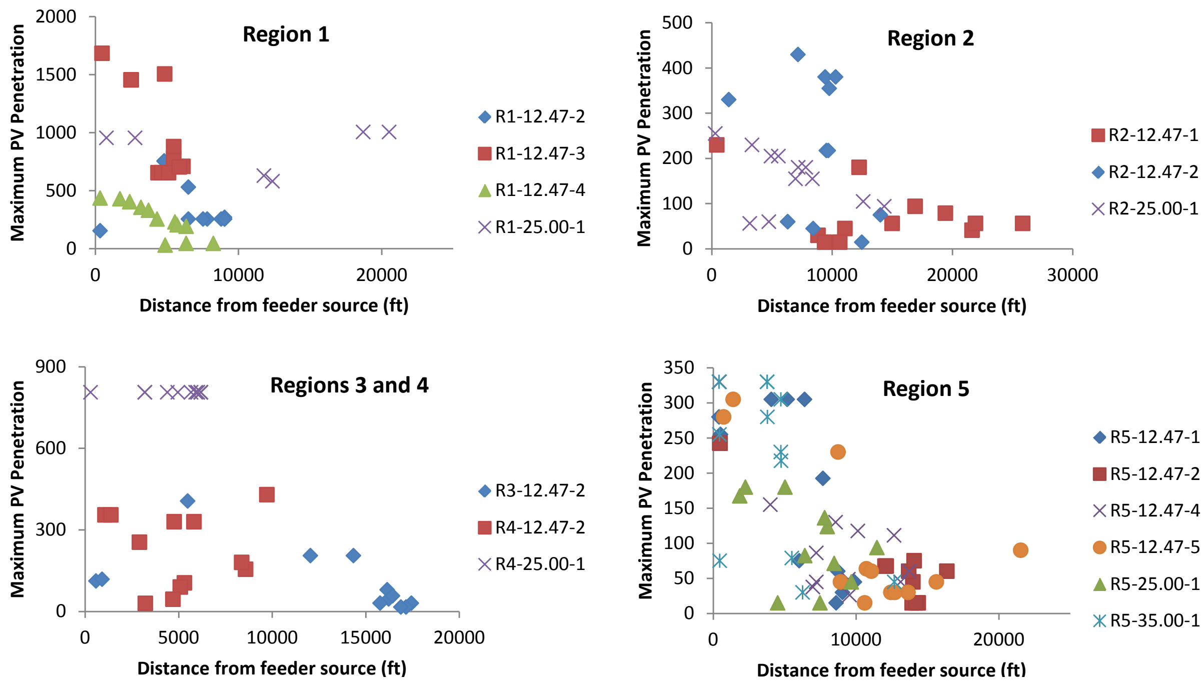


Fig. 7. Maximum PV penetrations plotted against conductor distance from PV system to feeder source, by geographic region.

Fig. 8 shows the maximum PV penetrations for each feeder under each non-random location scenario. Results over 500% are truncated to provide better resolution for more realistic penetrations. For single PV systems, more scenarios are limited by current than in the distributed PV scenarios. This is because the requirement that the system be installed at a three-phase node increases the probability of selecting a node near the trunk of the feeder where voltage is less likely to be an issue.

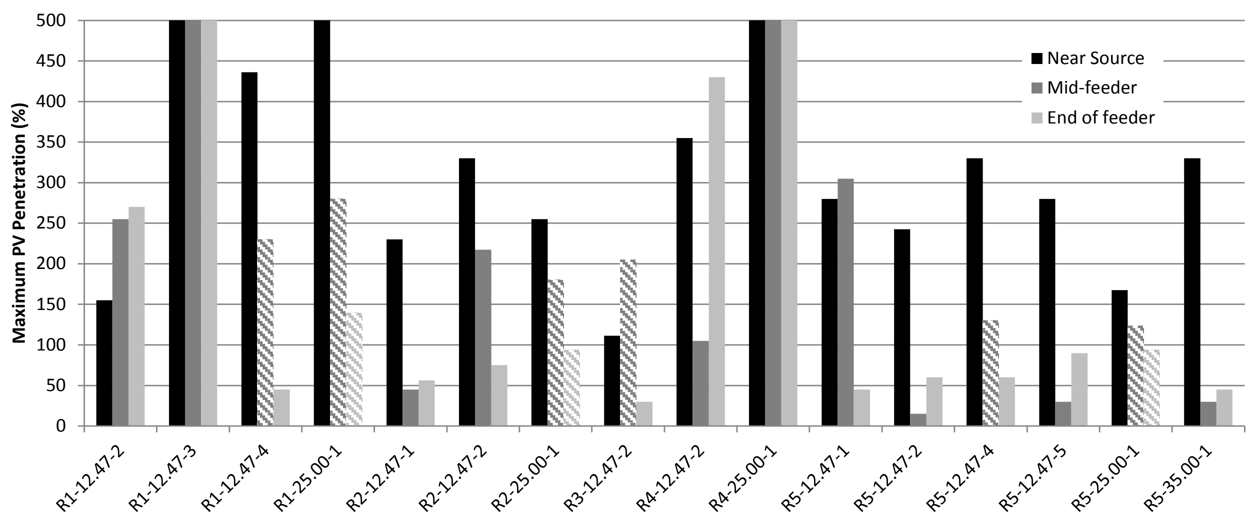
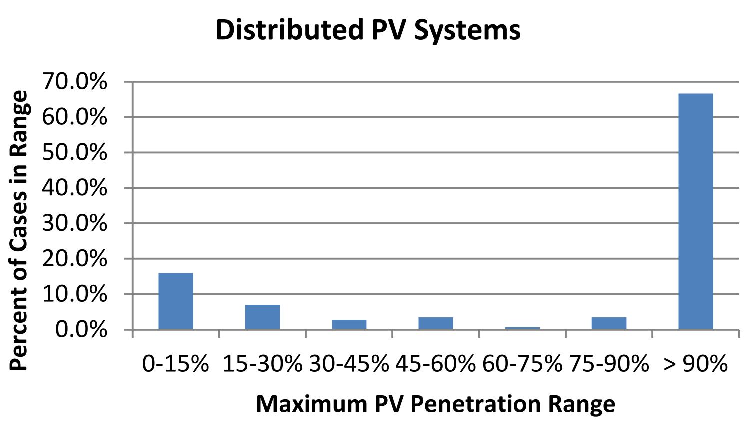


Fig. 8. Maximum PV penetration for the 16 taxonomy feeders with single PV systems. Solid columns indicate PV penetration was limited by overcurrent and hatched columns indicate PV penetration was limited by overvoltage. Results over 500% are truncated.

V. Conclusions

In this paper, several trends have been noted when considering maximum PV penetration relative to steady-state voltage and overcurrent: For distributed PV systems, maximum PV penetration was nearly always above 50% unless the feeder already exhibited maximum load voltages on the very high end of ANSI range A without PV. Maximum PV penetration generally decreases as the distance from the feeder source to the PV system increases, but most feeders still tolerate moderate to high PV penetrations even for PV systems near the end of the feeder.

Fig. 9 illustrates the general trend of very high PV tolerance with a few notable exceptions. In 86% of all PV location scenarios on all feeders, the maximum PV penetration was above 30%. In two-thirds of cases, the maximum penetration was greater than 90%. This does not indicate that two-thirds of cases will actually tolerate greater than 90% PV penetration, but rather that steady-state voltage and current are not limiting factors in approximately two-thirds of cases. While the 15% penetration rule of thumb was found to be conservative in most cases (and sufficient in all single PV system cases), it was actually too high in 16% of the distributed PV cases.



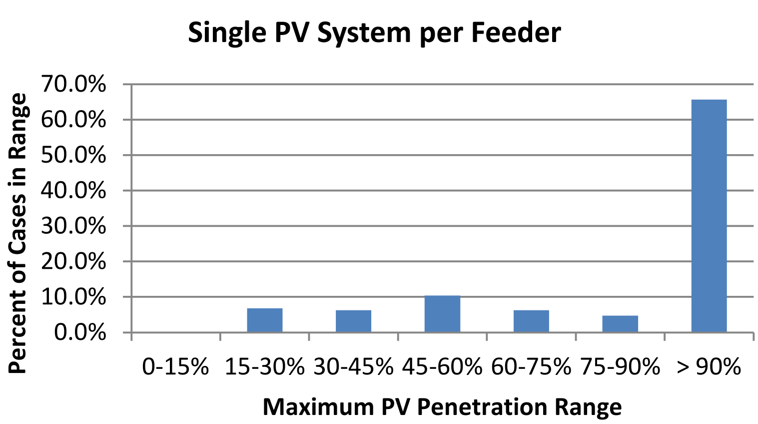


Fig. 9. Percentage of simulated cases in which maximum PV penetration fell in various ranges for distributed PV (top) and single PV systems (bottom).

References

[1] Masters, C.L., "Voltage rise: the big issue when connecting embedded generation to long 11 kV overhead lines," *Power Engineering Journal*, vol. 16, no. 1, pp. 5-12, Feb. 2002.

[2] Liu, Y.; Bebic, J.; Kroposki, B.; de Bedout, J.; Ren, W., "Distribution System Voltage Performance Analysis for High-Penetration PV," *IEEE Energy 2030 Conference, 2008*, Atlanta, Georgia. pp. 1-8, 17-18 Nov. 2008.

[3] Caples, D.; Boljevic, S.; Conlon, M.F., "Impact of distributed generation on voltage profile in 38kV distribution system," *2011 8th International Conference on the European Energy Market* May 25-27, Zagreb, Croatia. pp. 532-536, 25-27 May 2011.

[4] "IEEE Application Guide for IEEE Std 1547, IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems," *IEEE Std 1547.2-2008* , pp. 1-207, April 15 2009.

[5] Schneider, K.; Chassin, D.P.; Pratt, R.; Engel, D.; Thompson, S., "Modern Grid Initiative Distribution Taxonomy Final Report," PNNLNov 15, 2008. Accessed April 27, 2012: http://www.gridlabd.org/models/feeders/taxonomy_of_prototypical_feeders.pdf.

[6] Schneider, K.P.; Chassin, D.; Chen, Y.; Fuller, J.C., "Distribution power flow for smart grid technologies," *IEEE/PES Power Systems Conference and Exposition, 2009,* Seattle, Washington. pp. 1-7, 15-18 Mar. 2009.

[7] Slootweg, J.G.; Kling, W.L., "Impacts of distributed generation on power system transient stability," *IEEE Power Engineering Society Summer Meeting, 2002*, Chicago, Illinois. pp. 862-867, 25 July 2002.

[8] Begovic, M.; Pregelj, A.; Rohatgi, A.; Novosel, D., "Impact of renewable distributed generation on power systems," *Proceedings of the 34th Annual Hawaii International Conference on System Sciences,* Maui, Hawaii. pp. 654- 663, January 3-6, 2001.