Technical Evaluation of the 15% of Peak Load PV Interconnection Screen

Matthew J. Reno and Robert J. Broderick

Sandia National Laboratories, Albuquerque, NM, USA

***Abstract* — Most utilities use a standard small generator interconnection procedure (SGIP) process that includes a screen for placing potential PV interconnection requests on a fast track that do not require more detailed study. One common screening threshold is the 15% of peak load screen that fast tracks PV below a certain size. This paper performs a technical evaluation of the screen compared to a large number of simulation results for PV on 40 different feeders. Three error metrics are developed to quantify the accuracy of the screen for identifying interconnections that would cause problems or incorrectly sending a large number of allowable systems for more detailed study.**

***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 [1, 2], system losses [3], harmonics [4], increased wear to regulation equipment [5], voltage flicker [6], and protection [7, 8]. Therefore, before PV systems are allowed to interconnect with the grid, they must be studied to analyze and mitigate any impacts. These interconnection policies vary from utility to utility, but many utilities use a standard small generator interconnection procedure (SGIP) process for PV that includes a screen for placing requests on a fast track that do not require more detailed study [9-11]. One common interconnection screening threshold (IST) fast tracks PV smaller than 15% of peak load.

Previously, very little work has been done to research and perform technical evaluation of the interconnection screening methods. In [12], 100 small generator interconnection procedure (SGIP) studies were analyzed to determine if PV caused adverse impacts on the electric power system. In [13, 14], EPRI compared the minimum hosting capacity of 18 feeders to the 15% of peak load IST. This paper expands on that concept to a larger number of feeders and develops quantitative metrics for calculating the accuracy of the screening methods. Metrics will also be introduced to not only compare the screen to the feeder's minimum PV hosting capacity, but to also analyze the distribution of the feeder's locational hosting capacity and the number of violations and false-positives that the screen allows. This is an important concept because it analyzes the overall risk by how much of the feeder could handle various sized PV interconnections. There are many locations of a distribution system that can allow significantly more PV than the worst case location (feeder hosting capacity) or what is allowed by the IST.

II. Defining the Comparison Metrics

In order to calculate the accuracy of the 15% of peak load screen, metrics must be defined for comparison between the PV scenarios (sizes, feeders, and locations) that do not cause problems and the interconnection screen threshold (IST). The rest of this section explains the motivation for each error metric, provides the metric formulas, and demonstrates examples of the calculation. The figures in this section are only for demonstration purposes and are not reflective of any one distribution feeder or screening threshold.

A. Screen Accuracy Ratio (SAR)

The first metric investigates how close the IST is relative to the minimum hosting capacity (HC) for each feeder. The hosting capacity is determined for each feeder by using the methodology described in Section IV. Both the IST and HC will vary for each feeder depending on the load level, feeder characteristics, voltage regulator settings, etc. A screen accuracy ratio (SAR) of the two numbers will be used to determine the closeness of the screen to the first PV size that could potentially cause issues, equation (1).

$$SAR = \frac{HC - IST}{IST} * 100 \tag{1}$$

This number could be positive or negative, and it is similar to a percent error calculation with respect to the IST for how far it is above or below the HC. Like each of the error metrics defined in this paper, the optimal SAR value is near zero. Larger values for each of the error metrics means that the screen is performing worse. In the case of SAR, the value is hopefully positive. IST values should be designed to be conservative and smaller than the hosting capacity to ensure that any PV sizes and locations that could potentially cause issues are studied in more detail.

In order to provide graphical examples of the error metric calculations, figures similar to [15, 16] are used to show the percent of scenarios at each PV size that would cause issues on the feeder. For example, in Figure 1 the hosting capacity is 2.3 MW because a PV of that size could be placed anywhere on the feeder without causing issues. In contrast, only 42% of the locations on the feeder could support a 10 MW PV system without violations. In Figure 1, the SAR is approximately equal to 70%, meaning that the IST could be raised by 70% for this example system. In Figure 2, the IST is higher than the HC, and SAR≈-40%, meaning that the IST should be lowered by 40%.

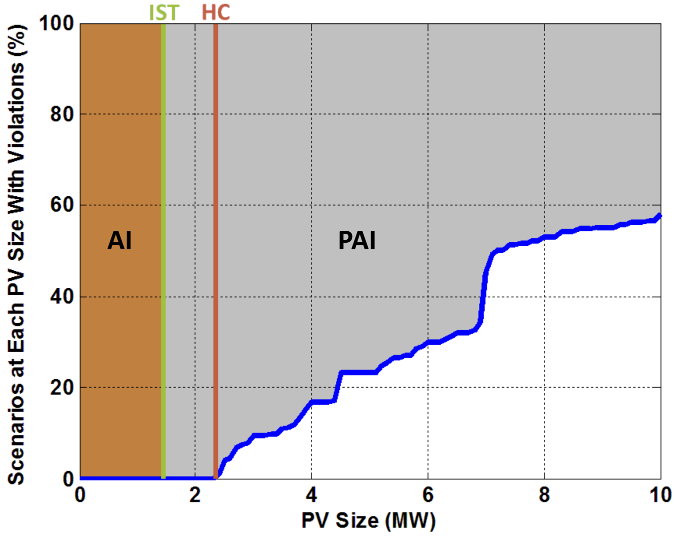

Figure 1. Example of an interconnection screen threshold (IST) with many potential allowable interconnections (PAI) beyond the allowed interconnections (AI).

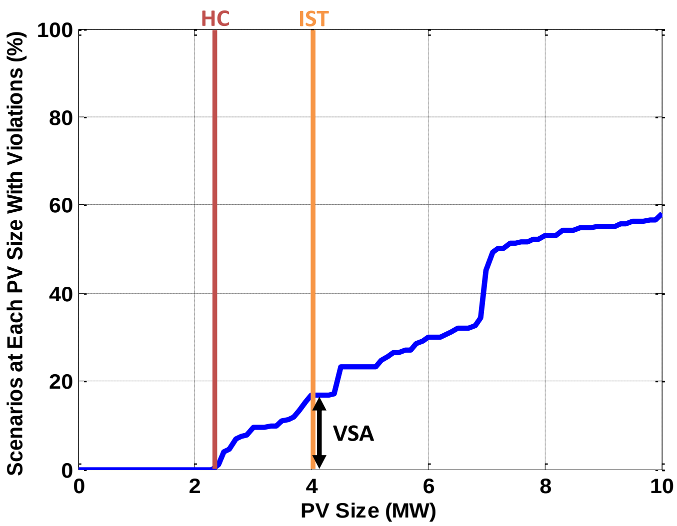

Figure 2. Example of an interconnection screen threshold (IST) that passes PV systems that cause violations the screen allowed (VSA).

B. *Violations the Screen Allowed (VSA)*

For the case that SAR is negative, this is caused by the IST being too high. When this occurs, the screening criteria will pass potential PV interconnections that will cause violations on the feeder. This is a serious issue because these PV systems will not be studied in detail, and could have potential impact to the system power quality and reliability. These impacts would normally be analyzed and mitigated during the interconnection process unless the system is fast tracked by the IST.

This error metric is simply the number of violations the screen allowed (VSA). For the example in Figure 2 where the IST is higher than the HC, the VSA is approximately 17% and is marked with a black arrow.

C. *Potential Percent Increase (PPI)*

While SAR provides information about the interconnection screen's accuracy to the feeder hosting capacity, it does not represent how many potentially allowable interconnections (PAI) should have been passed by the screening method because they would not cause any issues. These false positives in the screening process provide the motivation for more accurate screening methods that detect interconnections without violations beyond the allowed interconnections (AI). A large PAI means that the screen is sending a larger number of interconnection requests to a more detailed study than is necessary, which increases the labor and costs to the utility. In general, the PAI could be decreased by including more locational information into the IST, such as distance to the substation.

Both the AI and PAI are essentially areas calculations as shown in Figure 1. The potential percent increase (PPI) in (2) is a ratio of PAI to AI that shows the dramatic number of PV interconnection that could have been allowed by the screen relative to the number that it currently allows.

$$PPI = \frac{PAI}{AI} * 100 \tag{2}$$

III. Feeders Analyzed

A large database of feeders has been analyzed to validate the 15% of peak load screen. This ensures that the results of the accuracy of the IST are not specific to only one feeder or only specific types of feeders.

For this analysis, 40 real feeders from various utilities around the United States were simulated using the detailed methodology described in Section IV. The 40 feeders range in length from 1.8 km to 29.4 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. Of course the feeder peak load is highly correlated with the voltage class of the feeder. The range of 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 (kV)	4	12	12.47	13.2	16	19.8	20.78	33	34.5
Number of Feeders	2	16	15	1	1	1	2	1	1

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

The majority of the feeders (31 of 40) have no voltage regulators inside the feeder itself, but as seen in Figure 3, there can be up to 6 regulators per feeder. In total, there are 25 voltage regulators in the database of 40 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.

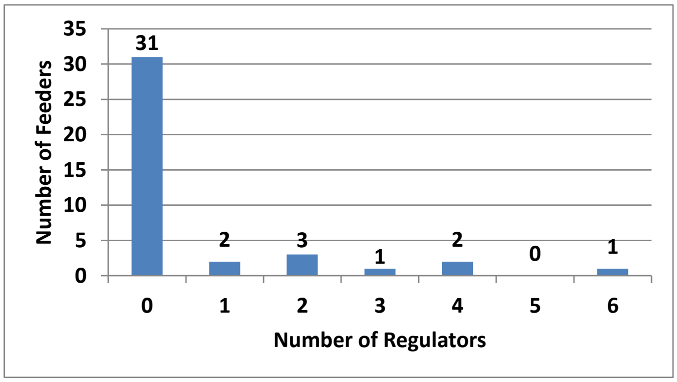

Figure 3. Histogram of the number of voltage regulators on each of the 40 feeders.

Both the fixed and switching capacitors are modeled for each feeder. As seen in Figure 4, the feeders have between 0 to 7 capacitors per feeder. The feeder with 7 capacitors has a total of 9.9 MVAR of capacitance on the feeder. Most of the switching capacitors are voltage-controlled, but there are also time-controlled, temperature-controlled, kVAR-controlled, time-biased voltage-controlled, and seasonally-controlled capacitors.

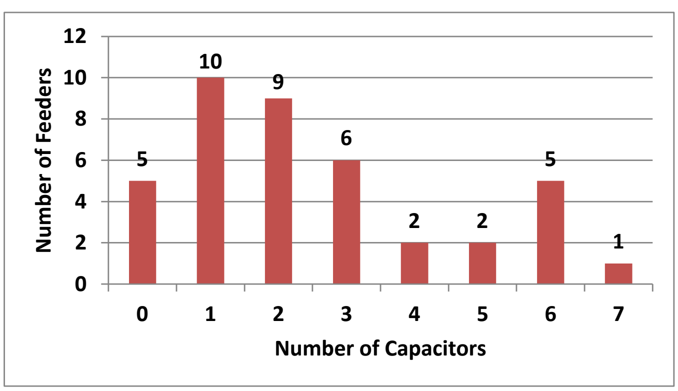

Figure 4. Histogram of the number of capacitors on each of the 40 feeders.

IV. Detailed PV Analysis Methodology

In order to validate the accuracy of the IST, it must be compared to a detailed analysis of the PV interconnection to determine if there is any impact to the operation of the distribution system. For this purpose, a large number of potential PV scenarios (combinations of PV size and location) are investigated using the methodology in [15, 16]. All simulations are performed in OpenDSS [17] using GridPV [18]. On average, there are around 40,000 PV scenarios analyzed per feeder.

For each PV scenario, a series of simulations is performed to detect any potential violations caused by the PV interconnection. Simulations are performed for a range of potential feeder load values that occur during daytime hours of 10am to 2pm in the year [9]. The focus is on voltage and thermal violations. Steady-state voltage violations are determined using ANSI C84.1, and thermal violations are defined as current flows greater than the amp rating of any device. Temporary over-voltages are also considered by simulating extreme up and down ramps in PV output in a faster time period than the voltage regulation equipment can react. Finally, at any given time period, there are many different states the feeder could be in as far as regulation equipment taps and switching capacitor states. All potential states of the feeder are simulated to detect for violations. After all the different power flow solutions have been solved for different states, load levels, and PV ramps, the PV scenario is defined as either being allowable or having violations.

With the detailed simulations, it is known if a particular PV interconnection could potentially cause issues to the operation of the feeder during the year. This defines the locational hosting capacity for how much PV can be put at the bus before violations occur. The locational PV hosting capacity for each bus is shown in Figure 5 for the 12.47 kV publically available distribution system Ckt5 [19]. Figure 5 also shows which type of violation (line loading or over-voltage) limited the locational PV hosting capacity.

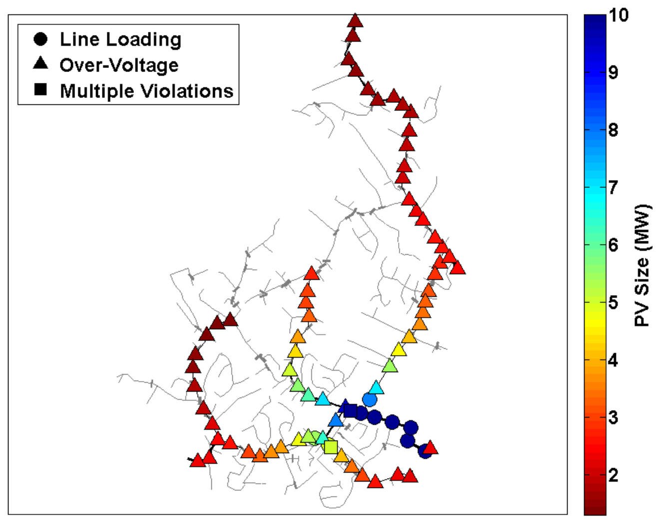

Figure 5. Ckt5 locational PV hosting capacity.

The PV impacts can also be shown using the feeder impact signature [16] shown in Figure 6. The feeder PV hosting capacity (HC) is shown in green for the largest PV that can be interconnected anywhere on the feeder without causing issues.

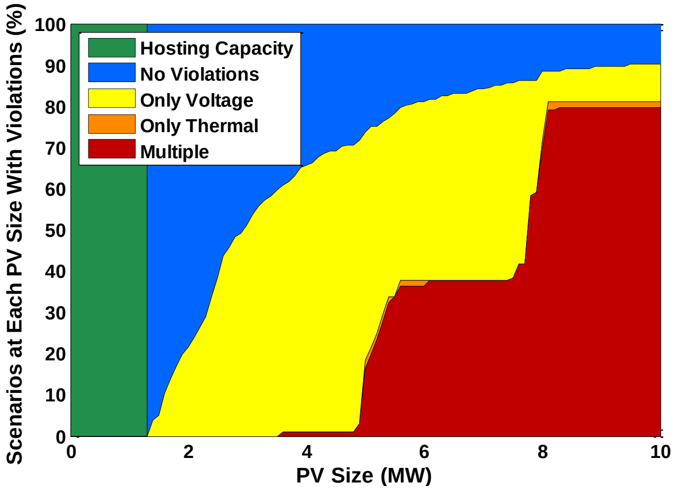

Figure 6. Ckt5 feeder risk impact signature.

This type of analysis is performed for each of the 40 feeders. The hosting capacity of each feeder is shown in Figure 7, along with which type of violation limited the PV hosting capacity.

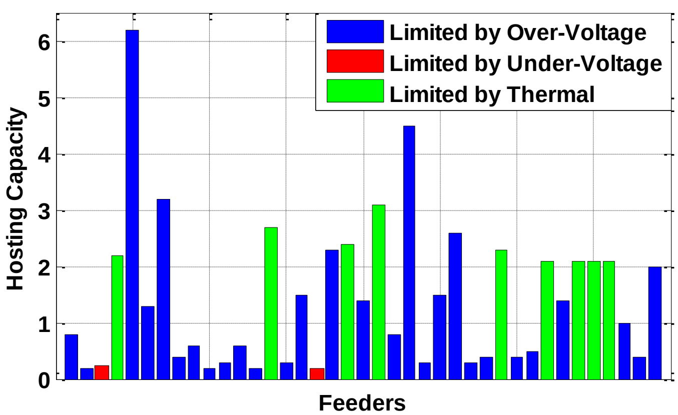

Figure 7. Hosting capacity of 40 feeders.

V. Results

A. *Screen Accuracy Ratio (SAR)*

The detailed analysis was performed for all 40 feeders to determine the first PV size that caused issues on the feeder, or the feeder hosting capacity. The results are compared to the 15% of peak load PV IST. These two numbers for each feeder are shown in Figure 8, sorted by the feeder peak load. Figure 8 also demonstrates that the feeder hosting capacity is not well correlated with the load.

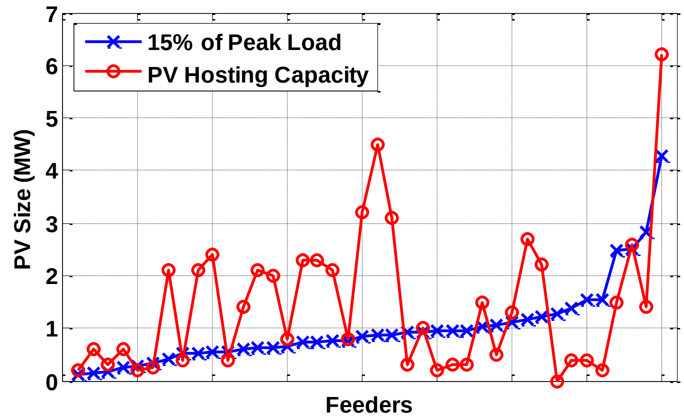

Figure 8. The 15% of peak interconnection screen threshold (IST) and the first PV size with issues (hosting capacity) for each feeder.

Figure 9 shows the hosting capacity vs. 15% of peak load IST for each feeder. To the upper left of the diagonal line represents the IST being larger than the HC, which is a negative SAR error value. The negative SAR values are concerning because the screen allows PV interconnections that would potentially cause problems. Feeders to the lower right in Figure 9 that are particularly far from the dashed black line would result in high SAR values, which means unnecessarily increased study time for the utility.

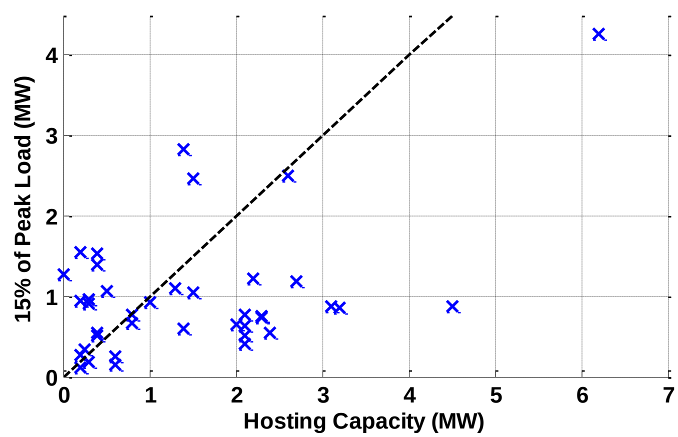

Figure 9. Comparison of hosting capacity vs. 15% of peak load IST.

The SAR error value is calculated for each feeder, and the distribution of errors for the 15% of peak load screen is shown in Figure 10. With a max of SAR=418%, the HC for that feeder is more than 4 times larger than 15% of peak screen. There is also a feeder with SAR=-95%, which means the IST is much higher than the feeder's hosting capacity. On average, SAR=83%.

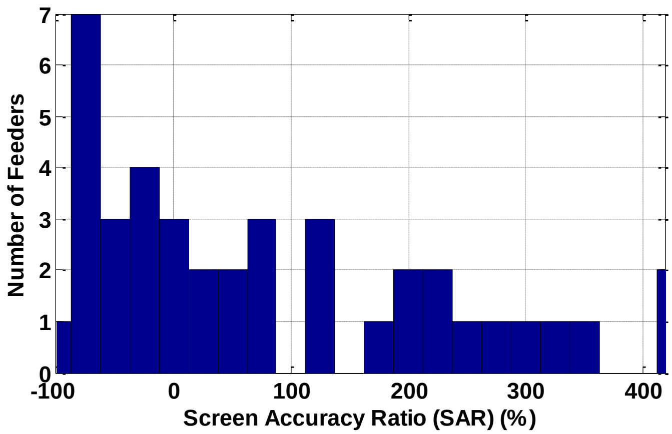

Figure 10. The screen accuracy ratio (SAR) error distribution for the 15% of peak load screen.

B. Violations the Screen Allowed (VSA)

The feeders with negative SAR values result in passing a certain number of PV interconnections that will cause operational problems on the distribution system. The violations the screen allowed (VSA) are calculated based on the percent of the feeder where a PV system that is 15% of peak load would have been problematic. Figure 11 shows the VSA error metric for each of the 40 feeders individually.

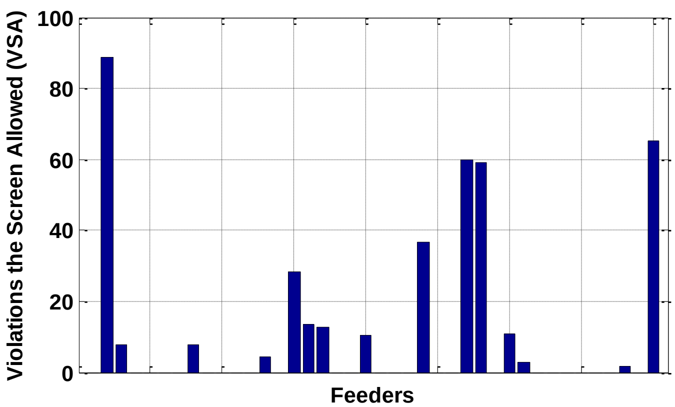

Figure 11. The VSA error metric for each feeder for the 15% of peak load IST.

While the screen accuracy ratio (SAR) is calculated by averaging the individual values for each of the 40 feeders, this method is not recommended to obtain the average VSA. SAR is a one to one comparison of feeder hosting capacity to feeder IST. On the other hand, VSA includes the percentage of the feeder that can support the PV interconnection size. In order to appropriately weight the violations based on feeder size, the violations the screen allowed (VSA) is calculated for all feeders together. For example, the 40 feeders have a total of 14,207 buses for potential PV placement. The VSA is the percent of all of those buses that, when connected with the maximum PV size allowed by the screen, will result in issues on the feeder. Creating the curve from Figure 2 for all feeders results in Figure 12.

Placing the maximum PV size allowed by the 15% of peak load screen randomly on one of the 14,207 buses of the 40 feeder will result in issues 22.1% of the time. The screen is obviously not conservative enough in certain cases and is passing PV interconnections that require a more detailed interconnection analysis.

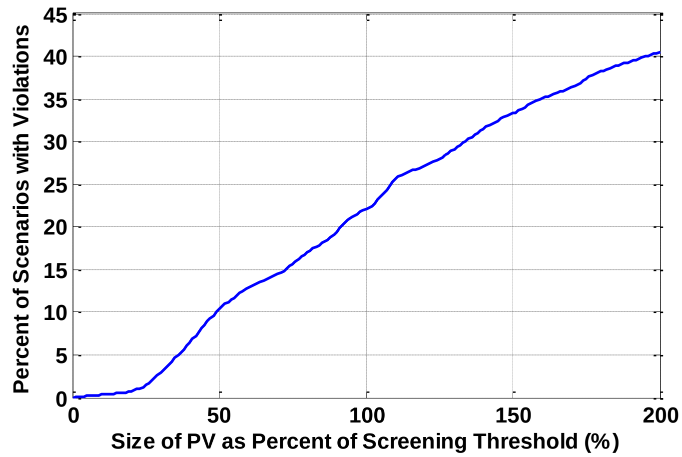

Figure 12. Violations the screen allowed (VSA) for the 15% of peak load interconnection screen threshold (IST).

C. Potential Percent Increase (PPI)

The final metric of potential percent increase (PPI) is not as significant as the first two metrics. It only represents the number of PV interconnections that could have been fast tracked but were not allowed by the IST. This is less of an error metric because it does not represent problems with the IST, just potential room for improvement.

Calculating the PPI per feeder can result in some extremely high values if the area of the allowed interconnections (AI) is small for a particular feeder. The individual PPI values are shown in Figure 13.

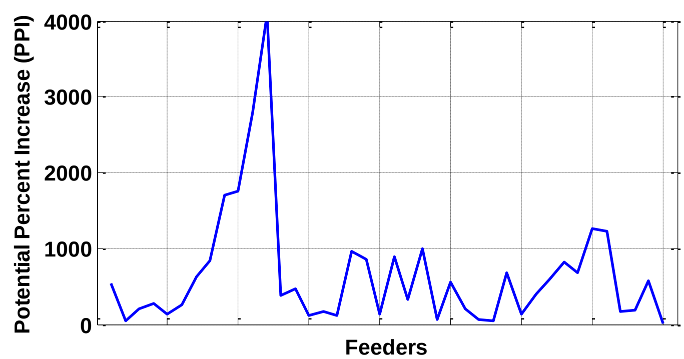

Figure 13. Potential percent increase (PPI) for each feeder.

Similar to the VSA metric, in order to calculate the average PPI for the metric, it is not appropriate to average the individual PPI for each feeder. Instead the allowed interconnections (AI) are summed across all feeders and divided by the summation of potentially allowable interconnections (PAI) of all feeders. The potential percent increase is more difficult to show graphically, but for the 15% of peak screen, the potential percent increase (PPI) results in 295% more potential PV interconnections that do not cause violations than are currently passed by the IST.

VI. Conclusions

This paper presented a novel analysis of the accuracy of the 15% of peak load PV interconnection screen compared to wide range of PV scenarios on 40 different real distribution feeders. The quantitative accuracy of screening methods has not been previously well studied, especially for a large database of feeders. Three new error metrics were developed to quantify the accuracy of the screening method for identifying interconnections that would cause problems or incorrectly send a large number of allowable systems for more detailed study.

With a screen accuracy ratio SAR=83%, the minimum PV size that will cause any issues is twice as high as the 15% screen on average. The violations the screen allowed VSA=22.1% demonstrates that the screen is passing a considerable percentage of interconnections that could cause problems. Finally, the potential percent increase PPI=295% shows the significant potential for improvement in more advanced screening methods.

In the future as advanced inverter functionality like volt/var becomes more common, many potential impacts of PV can be mitigated. For example, all feeders in blue in Figure 7 that are limited by over-voltage violations would have increased hosting capacity with volt/var [20]. Future work will include investigating the accuracy of the 15% of peak load IST with smart inverters, in addition to studying other interconnection screening methods.

VII. References

[1] A. Hoke, R. Butler, J. Hambrick, and B. Kroposki, "Steady-State Analysis of Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders," *IEEE Transactions on Sustainable Energy,* 2012.

[2] J. Quiroz, M. J. Reno, and R. J. Broderick, "PV-Induced Low Voltage and Mitigation Options," in *IEEE Photovoltaic Specialists Conference*, 2015.

[3] D. T. Rizy, L. Fangxing, L. Huijuan, S. Adhikari, and J. D. Kueck, "Properly understanding the impacts of distributed resources on distribution systems," in *IEEE PES General Meeting*, 2010, pp. 1-5.

[4] J. C. Hernández, M. J. Ortega, J. De la Cruz, and D. Vera, "Guidelines for the technical assessment of harmonic, flicker and unbalance emission limits for PV-distributed generation," *Electric Power Systems Research,* vol. 81, pp. 1247-1257, 2011.

[5] J. E. Quiroz, M. J. Reno, and R. J. Broderick, "Time Series Simulation of Voltage Regulation Device Control Modes," in *IEEE Photovoltaic Specialists Conference,* 2013.

[6] E. M. Stewart, T. P. Aukai, S. D. J. MacPherson, B. P. Quach, D. Nakafuji, and R. Davis, "A realistic irradiance-based voltage flicker analysis of PV applied to Hawaii distribution feeders," in *IEEE Power and Energy Society General Meeting*, 2012, pp. 1-7.

[7] H. Ravindra, M. O. Faruque, P. McLaren, K. Schoder, M. Steurer, and R. Meeker, "Impact of PV on distribution protection system," in *North American Power Symposium*, 2012.

[8] J. Seuss, M. J. Reno, R. J. Broderick, and S. Grijalva, "Maximum PV Size Limited by the Impact to Distribution Protection," in *IEEE Photovoltaic Specialists Conference*, 2015.

[9] M. Coddington, B. Mather, B. Kroposki, K. Lynn, A. Razon, A. Ellis, *et al.*, "Updating Interconnection Screens for PV System Integration," National Renewable Energy Laboratory NREL/TP-5500-54063, 2012.

[10] K. Fox, S. Stanfield, L. Varnado, T. Culley, M. Sheehan, and M. Coddington, "Updating Small Generator Interconnection Procedures for New Market Conditions," National Renewable Energy Laboratory NREL/TP-5500-56790, 2012.

[11] R. J. Broderick and A. Ellis, "Evaluation of alternatives to the FERC SGIP screens for PV interconnection studies," in *IEEE Photovoltaic Specialists Conference*, Austin, TX, 2012.

[12] S. S. Sena, J. E. Quiroz, and R. J. Broderick, "Analysis of 100 utility SGIP PV interconnection studies," in *IEEE Photovoltaic Specialist Conference (PVSC)*, 2014, pp. 1005-1010.

[13] J. Smith, "Hosting Capacity Analysis and New Screening Methods for PV," presented at the PV Distribution System Modeling Workshop, Santa Clara, CA, 2014.

[14] "Distributed Photovoltaic Feeder Analysis: Preliminary Findings from Hosting Capacity Analysis of 18 Distribution Feeders," EPRI, Technical Report 3002001245, 2013.

[15] K. Coogan, M. J. Reno, and S. Grijalva, "Locational Dependence of PV Hosting Capacity Correlated with Feeder Load," in *IEEE PES Transmission & Distribution Conference & Exposition*, 2014.

[16] M. J. Reno, K. Coogan, S. Grijalva, R. J. Broderick, and J. E. Quiroz, "PV Interconnection Risk Analysis through Distribution System Impact Signatures and Feeder Zones," in *IEEE PES General Meeting*, National Harbor, MD, 2014.

[17] EPRI. (2015). *Open Distribution System Simulator (OpenDSS)*. Available: http://sourceforge.net/projects/electricdss/

[18] M. J. Reno and K. Coogan, "Grid Integrated Distributed PV (GridPV) Version 2," Sandia National Labs SAND2014-20141, 2014.

[19] EPRI. (2015). *EPRI Test Circuits*. Available: http://ewh.ieee.org/soc/pes/dsacom/testfeeders/

[20] J. Seuss, M. J. Reno, R. J. Broderick, and S. Grijalva, "Improving Distribution Network PV Hosting Capacity via Smart Inverter Reactive Power Support," in *IEEE PES General Meeting*, Denver, CO, 2015.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.