Locational Sensitivity Investigation on PV Hosting Capacity and Fast Track PV Screening

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***Abstract*—A 15% PV penetration threshold is commonly used by utilities to define photovoltaic (PV) screening methods where PV penetration is defined as the ratio of total solar PV capacity on a line section to peak load. However, this method doesn't take into account PV locational impact or feeder characteristics that could strongly change the feeder's capability to host PVs. This paper investigates the impact of PV location and phase connection type on PV hosting capacity, and then proposes a fast-track PV screening approach that leverages various PV hosting capacity metric responding to different PV locations and types. The proposed study could help utilities to evaluate PV interconnection requests and also help increase the PV hosting capacity of distribution feeders without adverse impacts on system voltages.**

***Index Terms* — Photovoltaic, PV screening, hosting capacity, voltage improvement, distribution system.**

I. Introduction

VARIOUS incentive mechanisms have stimulated the installation of solar PVs for both commercial and residential applications. To ensure an ongoing stable and reliable operation of the grid, utilities must evaluate these interconnection requests before approving PV integrations. A 15% threshold [1] that is defined as the ratio of PV capacity on a line section to peak load is used by most utilities to develop their initial, fast track, PV screenings. However, this criterion does not take into account PV locational impact or feeder characteristics.

Hosting capacity is defined as the total PV capacity that can be accommodated on a given feeder without adversely impacting voltage, protection and power quality and with no feeder upgrades or modifications. Some existing studies [2]-[5] have shown that the PV penetration level depends on feeder length, regulation, PV location, operating practices, etc. However, there is no detailed sensitivity study of PV locations, types and phases on PV hosting capacity, which is significant with regards to developing effective PV screens for utilities to help increase PV hosting capacity and avoid adverse impacts.

This paper investigates the sensitivity of PV hosting capacity with respect to PV locations and phase connection type among various distribution feeders. At the present study stage, voltage limits including overvoltage, voltage deviation and voltage unbalance are considered as the evaluation criteria to define the allowed maximum PV capacity in the feeder. Based on the results of this investigation, a fast PV screening approach is developed to leverage various PV hosting capacities responding to different PV locations and types.

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II. Feeder Characteristics And PV Deployment

Fig.1 shows some key characteristics of seven test feeders, including voltage class, feeder length, feeder maximum impedance magnitude, peak load and the existence of line voltage regulators. Feeder 1 is 4 kV and all other feeders are 12 kV. Feeder 4 is the longest feeder with the maximum impedance among six test feeders. Feeders 4 and 5 have line regulators. Feeders 1-6 are used to investigate the sensitivity of PV hosting capacity to PV locations and types, and feeder 7 is reserved to validate the investigation result and the proposed fast track screen.

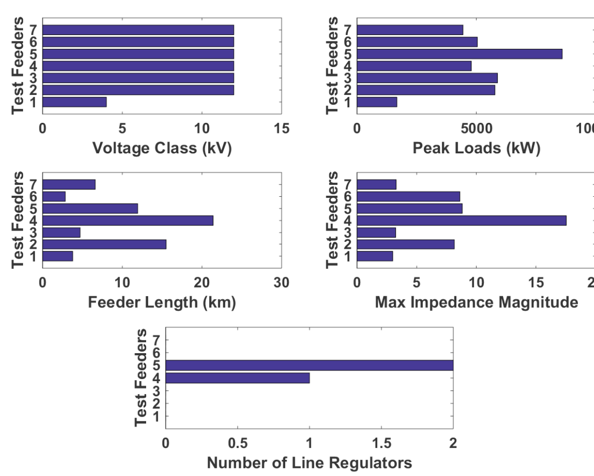

Fig. 1. Key characteristics of six test feeders.

Fig. 2 describes the procedure to generate PV deployments into test feeders, which is based on Monte Carlo simulation. At first, all candidate PV customers are determined according to certain rules based on customer location and phase type. Then, PV locations are selected randomly from candidate customers, and each PV location will be assigned one aggregate PV unit installation. PV type (residential or commercial) is decided by the type of customer load. This paper studies the hosting capacity of small-scale rooftop PVs, and the probability density functions of both residential and commercial PV maximum power are acquired from California solar PV statistics data and then sampled randomly to determine the capacity of each

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installed PV unit. Such a procedure is repeated to increase PV customer penetration by a fixed step (e.g. 2% or 4% of total customers) until 100% PV customer penetration achieved. At each deployment step, system voltages are evaluated to check whether any violations have occurred. The above methodology was developed by EPRI and is described in [6]. Table I shows the voltage limits regarding overvoltage, voltage deviation and voltage unbalance, based on ANSI C84.1 standard [7]. This paper only considers primary voltage because primary voltages are of most significant concern to utilities and it is relatively easy to upgrade secondary circuits should violations occur.

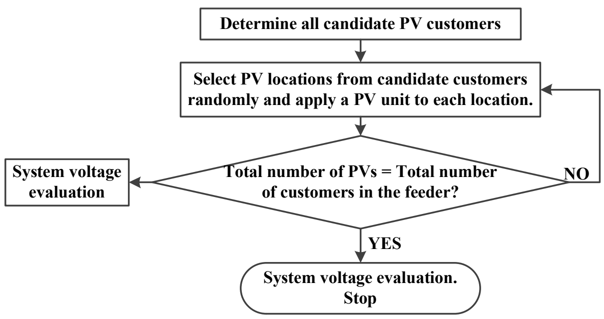

Fig. 2. The procedure of generating PV deployments into the test feeder.

TABLE I
VOLTAGE LIMITS FOR EVALUATING PV HOSTING CAPACITY

Criterion	Description	Threshold
Overvoltage	Voltage magnitude.	1.05 pu
Voltage Deviation	Deviation in voltage from no PV case.	0.03 pu at primary 0.05 pu at secondary
Unbalance	Phase voltage deviation from average.	0.03 of phase voltage

III. LOCATIONAL SENSITIVITY ANALYSIS

Candidate PV customers should be determined first to proceed with the voltage evaluation for different PV penetration levels. The rule to determine candidate PV customers is actually the screen that is potentially used by utilities to make a decision for the PV interconnection request. In order to study the locational sensitivity of PV hosting capacity, three approaches are used to determine the candidate PV customers, including 1) the impedance magnitude of the customer primary bus from the substation; 2) the distance of the customer from the substation; 3) the ratio between single-phase PV power and three-phase PV power.

Afterwards, the procedure given in Fig. 2 is used to generate PV deployments and evaluate voltage violations until reaching 100% PV customer penetration, and such a study is repeated 100 times. For each test feeder, two loading scenarios including maximum daytime load (10:00 am – 2:00 pm) and minimum daytime load are studied. All algorithms are programed using MATLAB, while the power flow is solved using OpenDSS [8].

A. *Candidate PV Customer Selection Based On Impedance*

This study investigates the impact of short-circuit impedance of PV locations on PV hosting capacity. The maximum magnitude of short-circuit impedances to all buses in six test feeders are summarized in Fig. 1. A threshold value need be defined first. If the short-circuit impedance magnitude of the customer is smaller than the threshold, this customer will be considered as a candidate PV customer. With various thresholds, the results of candidate PV customers will be different. A group of thresholds (0.1, 0.2, …, 1 of max impedance) are applied for each test feeder, and the corresponding studies following Fig. 2 are carried out to obtain the voltage results, respectively.

Based on 100 groups of results under two loading scenarios, Fig. 3 shows the existing PV power when the 1st violations occur in voltage magnitude (yellow bar) and voltage deviation (blue bar) for different thresholds, respectively. Some values are missing because there is no candidate customer within the defined threshold. For all feeders and all thresholds, the results of voltage unbalances are all within limits.

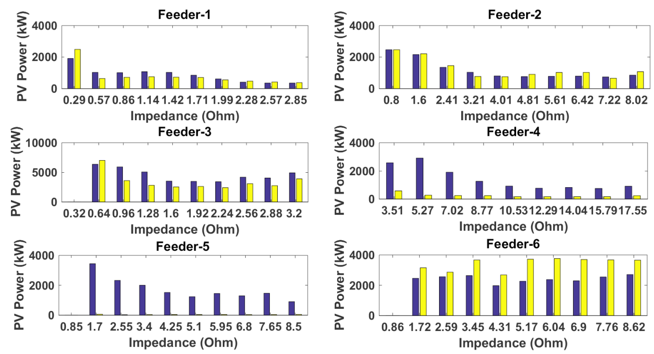

Fig. 3. Total existing PV power when the 1st voltage violation occurs based on impedance selection.

In general, a feeder could host more PV power without voltage violations if the impedances to all PV customers are small. For feeder 6, the existing PV powers under different thresholds are similar because the short-circuit impedances of all customer buses are all within 43.3% of the maximum impedance of all buses. Thus, the candidate PV locations don't change when the pre-defined threshold exceeds 0.5 of maximum impedance.

With the exception of feeders 4 and 5, the existing PV power when voltage magnitude and voltage deviation have the first violations are close. However, feeders 4 and 5 both have overvoltage violations under very low PV penetration. Compared with other feeders, these two feeders have line regulators, and it is usually the case that that a distribution feeder with a line regulator indicates that that feeder is more likely to have voltage problems and thus have a low PV hosting capacity.

Feeder 3 has the lowest impedance among all 12 kV test feeders, and its PV hosting capacity is the highest. On the other hand, the impedance of feeder 1 is lower than feeder 3 but feeder 1 has lower voltage class, and the PV hosting capacity of feeder 1 is lower. Thus it is indicated that the feeder with lower voltage class has relatively lower PV hosting capacity.

PV hosting capacity is finally decided by the existing PV power when the first voltage violation occurs, and it can be represented using the percentage of total peak loads. As a result, PV hosting capacity of six test feeders along with the allowed maximum impedance magnitude of all PV customers is summarized as Fig. 4. The data of feeder-6 after 4.31 km are not included because they are actually noise that could not represent the pattern in the correct way. In summary, Fig. 4 shows that PV hosting capacity is attenuating with the increase of impedance of PV locations.

If feeders 4 and 5 are neglected, PV hosting capacity is always greater than 15% of peak loads as long as the short-circuit impedance magnitudes of all PV locations are less than 3.2Ω. In addition, PV hosting capacity can be close to 35% when the impedance magnitudes of all PV locations are less than 2 Ω approximately.

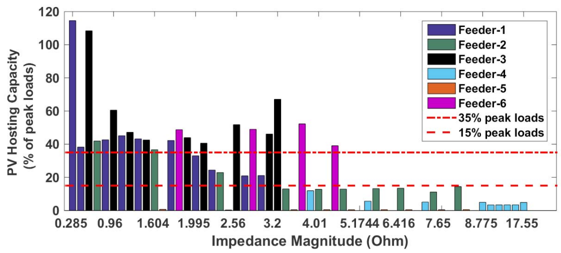

Fig. 4. PV hosting capacity of six test feeders based on impedance screen.

B. *Candidate PV Customer Selection Based On Distance*

This study investigates the changes in PV hosting capacity in relation to the distances of PV locations from the substation. If the distance of a customer from the substation is within the pre-defined threshold, this customer will be considered as a candidate PV location. Similarly, a group of thresholds (0.1, 0.2, …, 1 of max distance) are applied for each test feeder, and the corresponding studies following Fig. 2 are carried out to obtain the voltage results, respectively.

Fig. 5 shows the total existing PV power when the first violations occur in voltage magnitude (yellow bar) and voltage deviation (blue bar) for different thresholds, respectively. There are still no violations in voltage unbalances.

With the exception of feeder-6, all other feeders could host much more PV power if the distances of all PV locations are closer to the substation. Feeders 4 and 5 still have overvoltage problem easily when PVs are interconnected.

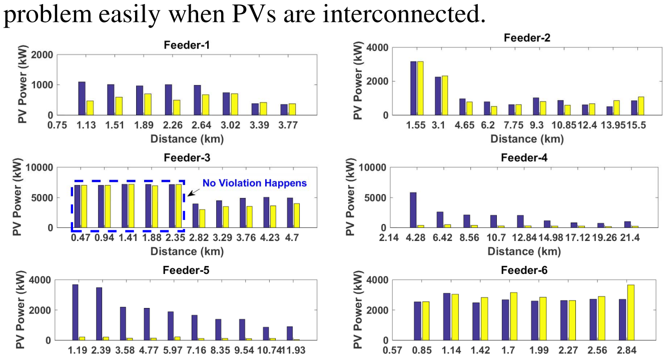

Fig. 5. Total existing PV power when the 1st voltage violation occurs based on distance selection.

There are never voltage violations in feeder-3 even at very high levels of PV penetration if all PV locations are within 2.35 km. Instead, if the distances of some PV locations exceed 2.35 km, voltage violations could occur at much lower PV penetration. This could be an indication that there must be a weak region after 2.35 km distance in feeder 3. Fig. 6 shows system topology and distance distribution of customers in feeder-3. The customers within the black dash circle are "safe" locations because their PV interconnections have no adverse impacts on system voltages, however, the customers within the red dash circle are "dangerous" locations since voltage limits will get violated easily if PV interconnection occurs at these locations beyond the "safe" locations.

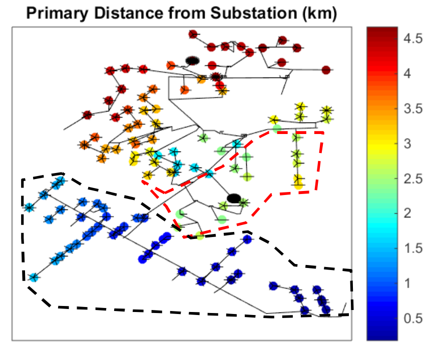

Fig. 6. System topology and distance distribution of customers in feeder-3.

After combining the results of six test feeders, Fig. 7 shows PV hosting capacity for different distance thresholds. Much higher PV hosting capacity could be obtained if all PV locations are closer to the substation. Neglecting feeders 4 and 5, PV hosting capacity could be 15% of peak loads without voltage violations if all PVs are within 4.23 km. If all PVs are within 3.2 km, PV hosting capacities of 12 kV feeders 2, 3, 6 are always greater than 40%, and the hosting capacity of 4 kV feeder 1 is greater than 30%.

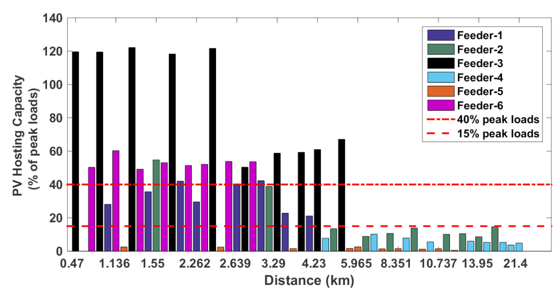

Fig. 7. PV hosting capacity of six test feeders based on distance screen.

C. *Candidate PV Customer Selection Based On PV Phases*

This study investigates the impact of PV phases on changing PV hosting capacity. Primarily, the "phase ratio" is defined as

$$Phase\ Ratio = \frac{Total\ Power\ of\ single\ phase\ PVs}{Total\ PV\ power\ in\ the\ feeder} * 100\% \quad (1)$$

At first, PV locations are selected randomly from all customers until the total PV power reaches 15% of peak loads. Then, each PV deployment is only allowed if the phase ratio is still under the pre-defined threshold after the interconnection of new PV. In this manner, PV deployments are generated until 100% PV penetration obtained. The threshold is defined as 0.1, 0.2, 0.3, …, 1, respectively, and the corresponding PV hosting capacity is analyzed for six test feeders.

Figure 8 shows the total existing PV power of six test feeders when the first violations occur at voltage magnitude and voltage deviation, respectively. "Random" represents the base case when all customers are considered as candidates. Feeders 4 and 5 still have overvoltage problems at very low PV penetration, but they can always host PV power beyond 15% of peak loads without violations in voltage deviation.

Feeders 3 and 6 are the two shortest feeders among all 12 kV test feeders, and their PV hosting capacities are always over 45% of peak loads when restricting phase ratio from 10% to 100%. The hosting capacity of feeder 2 is over 15% of peak loads if the phase ratio is lower than 80%. PV hosting capacity of feeder 1 is always over 17%.

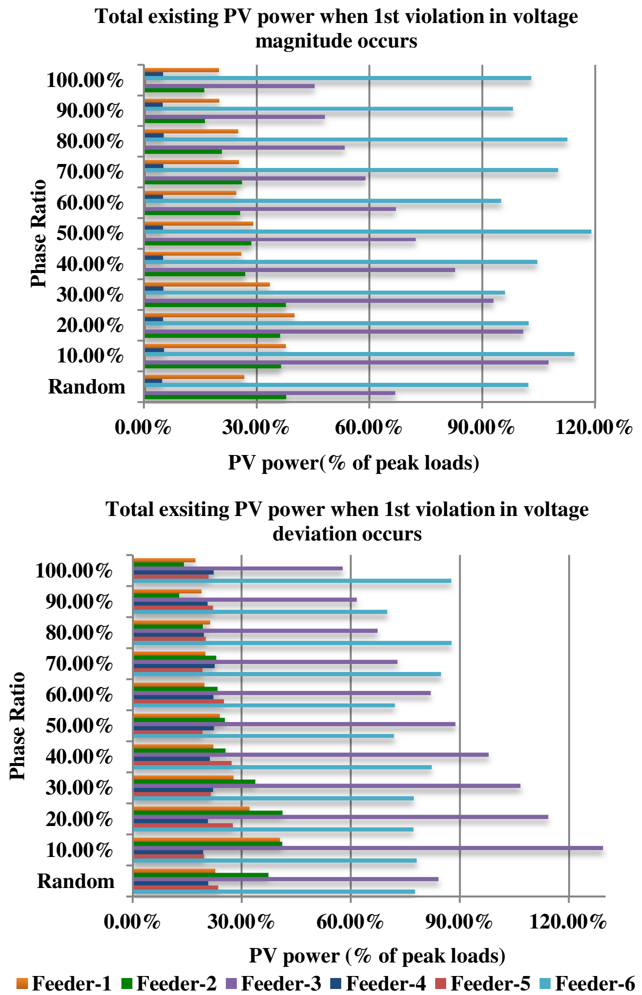

Fig. 8. Total existing PV power when the first voltage violation occurs based on PV phase selection.

In addition, Fig. 8 shows that the hosting capacity of feeder 3 is linearly decreasing and the hosting capacity of feeder 2 is also monotonously decreasing, with the increment of phase ratio thresholds. However, PV hosting capacities of all other feeders don't change much under different thresholds. In order to analyze the mechanism causing different behaviors of these feeders, the distance distributions of all customers in feeders 2 and 3 are plotted in Fig. 9. It can be observed that three-phase customers are clustered closely to the substation, compared with the locations of single-phase customers. With the increasing phase ratio, the locations of candidate PV customers are moving from the substation, and PV hosting capacity decreases. Thus, this result confirms the pattern concluded from the distance sensitivity study.

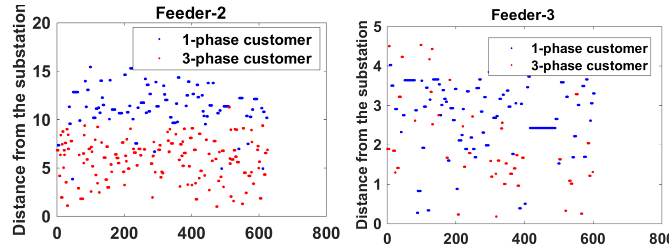

Fig. 9. Distances of all customers from the substations in feeders 2 and 3.

D. *Result Summary*

Based on the above investigation results, it is concluded that PV hosting capacity of a feeder is very sensitive to PV locations, and specifically four conclusions could be summarized as follows:

(1) PV hosting capacity could change greatly depending on the locations of PV customers. If all PV locations are close to the substation or the short-circuit impedance of all PV customers are small, a feeder could host more PVs without adverse impacts on system voltages.

(2) The voltage class of a feeder affects PV hosting capacity. In general, a feeder with higher voltage class could host more PVs without adverse impacts.

(3) If a feeder has line regulator, it could have overvoltage problems more easily when interconnecting PVs. This is because feeders with line regulators are generally long and weak.

(4) Short feeders with low short-circuit impedance has relatively high PV hosting capacity, which could be far beyond 15% of peak load.

IV. Fast PV Screen

Besides the four general conclusions drawn from the locational sensitivity study, regarding 12 kV feeders without line voltage regulators, the PV hosting capacity can be up to 35% of peak load if (i) the short-circuit impedance magnitudes of all PV customers are within 2 Ohm; or (ii) the distances to all PV customers from the substation are within 3.2 km. Additionally, the PV hosting capacity could be beyond 15% of peak loads if (i) the short-circuit impedance magnitudes of all PV customers are within 3.2 Ω; or (ii) the distances to all PV customers are within 4.23 km; or (iii) the proportion of single-phase PV power among all PV power is within 80%.

As a result, a fast PV screen could be developed and Fig.10 gives the flowchart of the approach. Each time when a PV tries to connect to the feeder, the three-step fast screen is conducted and the PV connection request will be approved if it could pass the screen. If the fast screen fails, further investigation is needed to determine whether to allow the connection. The proposed fast screen doesn't need complicated technical evaluation process, but it could allow the PV penetration up to 40% of peak load with all primary voltages within the limits.

In order to test the effectiveness of the fast PV screen, feeder 7 is used to apply the screening approach for each PV deployment, and its feeder characteristics are given in Fig. 1. Feeder 7 is 12 kV without line regulator, and it is also short with low impedance magnitude, compared with other test feeders. Thus, it is expected that its PV hosting capacity could be much higher than 15% of peak loads.

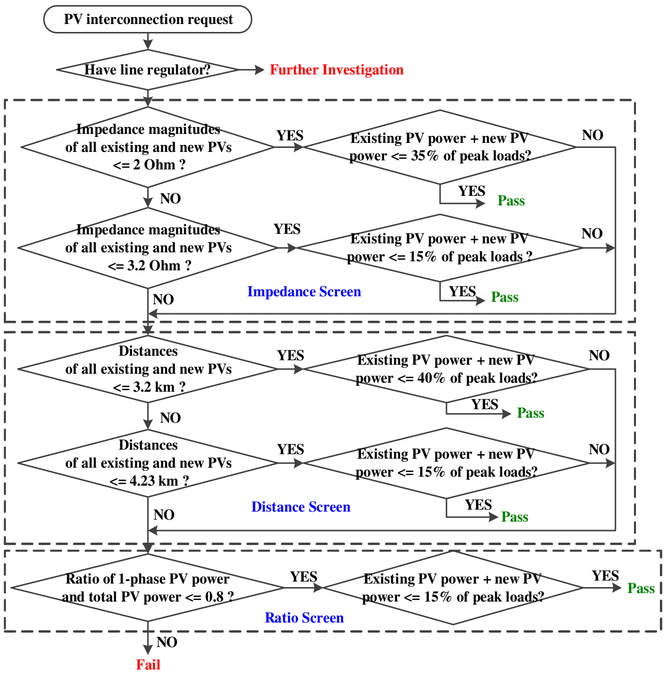

Fig. 10. Flowchart of the fast track PV interconnection screen.

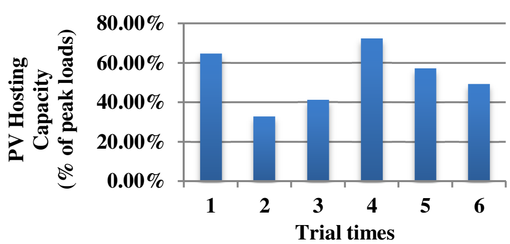

Fig. 11. PV hosting capacity of feeder-7 for different PV deployments.

At first, PV locations are randomly selected from all customers, and Fig. 11 gives the results of allowed PV power obtained for six trials. The highest PV hosting capacity is about 70% of peak loads, while the lowest value is around 32% of peak loads. Thus it further motivates the theory that PV hosting capacity is quite locational sensitive. But random PV interconnections could not always guarantee high PV penetration.

Instead, PV customers are still selected randomly one-by-one, but each PV customer must pass the fast track screen. When PV penetration reaches 40% of peak loads, PV deployment is stopped and all primary voltages are analyzed to check whether violations happen. The validation process is repeated 50 times and all voltage results have no violations. That is to say, PV penetration in feeder 7 can be as high as 40% without violating primary voltages with the aid of this fast track screen. Additionally, if more studies are conducted targeting at feeder 7, higher PV penetration could be ensured with different thresholds in fast track PV interconnection screen. Thus, compared with random deployment, the fast track PV screen can identify the promising PV interconnections and help increase PV hosting capacity.

Importantly, the specific thresholds given in Fig. 10 are not generic but only applicable to the test feeders used in this paper. However, the proposed locational sensitivity study and the framework of fast track PV screen are both applicable to all distribution feeders, and the thresholds of fast track PV screen corresponding to the specific feeders could be determined. Thus, this paper provides an effective approach for utilities to evaluate the PV hosting capacity of their own distribution feeders and make their own fast PV screens.

V. Conclusions

This paper studies the locational sensitivity of PV hosting capacity in distribution feeders. Monte Carlo simulation is used to determine PV hosting capacity by evaluating system voltages after interconnecting PVs. Three different approaches are used to select candidate PV customers, including an impedance based approach, a distance based approach and a phase ratio based approach. The results of all three approaches prove that PV hosting capacity is quite locational sensitive, and the higher PV hosting capacity could be obtained if PV interconnection locations are of shorter distance and smaller impedance. Besides, it proves that feeder characteristics including voltage class, the existence of line regulators and feeder length affects the PV hosting capacity greatly.

Furthermore, a fast PV screen is proposed according to the analysis conclusion of locational sensitivity study. This screen could identify feasible and promising PV locations that do not have adverse impact on system voltage, and could help increase PV hosting capacity.

VI. Acknowledgement

This work was supported by the U.S. Department of Energy under Contract No. DOE-EE0002061 with the National Renewable Energy Laboratory. The authors would also like to acknowledge Electric Power Research Institute (EPRI) for use of its DPV tool to accomplish parts of the analysis.

VII. Reference

[1] Electric Rule No. 21: Generating Facility Interconnections, Cal. P.U.C. 34818-E, January 2015.

[2] *Stochastic analysis to determine feeder hosting capacity for distributed solar PV*, Electric Power Research Institute (EPRI), Palo Alto, CA: 2012. 1026640.

[3] K. Coogan, M. Reno, S. Grijalva and R. Broderick, "Locational dependence of PV hosting capacity correlated with feeder load," *in the proceedings of 2014 IEEE PES T&D Conference and Exposition*, pp. 808-812, Chicago, 2014.

[4] J. Xiao, L. Bai, F. Li, H. Liang and C. Wang, "Sizing of energy storage and diesel generators in an isolated microgrid using discrete Fourier transform," IEEE Trans. Sustainable Energy, vol. 5, no. 3, Jul. 2014.

[5] R. Broderick and J. Williams, "Clustering Methodology for Classifying Distribution Feeders," presented at the 39th IEEE Photovoltaic Specialists Conference, Tampa Bay, FL, 2013.

[6] EPRI Distributed PV Monitoring and Feeder Analysis. Available at: http://dpv.epri.com/hosting_capacity_method.html.

[7] *American National Standard for Electric Power Systems and Equipment-Voltage Ratings (60 Hertz)*, NEMA ANSI C84.1-2011, 2011.

[8] EPRI OpenDSS, Open Distribution System Simulator, Program Sourceforge.Net, Available at: http://sourceforge.net/projects/electricdss/files/.