STREAMLINED METHOD FOR DETERMINING DISTRIBUTION SYSTEM HOSTING CAPACITY

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ABSTRACT

This document outlines the methodology of a streamlined analysis to determine the amount of photovoltaics that can be accommodated on a distribution network before adverse impacts occur (commonly termed hosting capacity). The solution can effectively be used in screening new interconnection requests as well as to estimate how much and where PV can be located such that grid upgrades are minimized. The method is being implemented in commercial distribution system analysis tools where it can be applied system-wide or on individual networks. The streamlined analysis of an individual network would take in the order of minutes compared to weeks for a detailed analysis. Application of the results include improved screening tools, visualization of hosting capacity constrained networks, and identification of problematic locations within a network. Speed and accuracy are mandatory, thus the methodology has been compared and validated to detailed analyses.

INTRODUCTION

Utility planning engineers at various locations throughout the world are experiencing an unprecedented number of photovoltaic (PV) interconnection requests [1]. Every interconnection request is unique as every network and PV system location is different. Since there is not enough time for the planning engineer to perform a detailed analysis of each proposed interconnection, simplified screens have been developed to assess the implications [2,3]. These screens, however, typically take the network model out of the analysis process which can severely limit the screens effectiveness. The planning engineer needs an analysis tool that is efficient yet effective.

This necessity to the screening process has led to the development of a streamlined method that is more advanced than simplified approaches yet not as intense as full detailed studies [4]. Detailed PV studies have been performed at the Electric Power Research Institute (EPRI) for over 30 unique networks [5,6]. Each network has been modelled from the substation down to the end-user. For these detailed analyses, all aspects of power quality and reliability issues have been examined to determine each network's hosting capacity. Hosting capacity is a network's ability to accommodate PV without adversely impacting reliability or power quality issues.

The lessons learned from these detailed studies have made it apparent that the detailed hosting capacity analysis can be transformed into a streamlined method. The streamlined hosting capacity method captures the electrical and consumer characteristics through load-flow and short-circuit analyses, runs through a sequence of impact studies, and then provides the network's ability to accommodate PV (hosting capacity). All of this occurs in a time-efficient and user-friendly manner.

This paper will elaborate on the streamlined hosting capacity methodology. This will also include results from the detailed analysis that support the development of the streamlined method along with a validation of the streamlined hosting capacity results with the results of the detailed studies.

BACKGROUND

The methods of the streamlined analysis are developed based on the stochastic detailed distributed PV (DPV) analyses conducted over the past several years at EPRI. To date, approximately 35 distribution networks have been analyzed with the rigorous approach outlined in [7,8]. The analysis examined the impact of small-scale (commercial/residential) and large-scale (utility class) PV. For each of these PV types, a wide range of issues have been examined, but voltage and protection issues are found to be the most affected. The thorough analysis of all networks has resulted in a database of approximately 6 million unique scenarios. The wealth of information derived from these detailed studies has led to the development and validation of the streamlined analysis methodology.

Issues Considered

Overvoltage at primary and secondary nodes are an issue as defined by ANSI standard C84.1. Voltage deviation limits at primary and secondary nodes are not defined in standards, but many utilities have their own threshold of what is considered acceptable in planning studies. Voltage deviations cover the range in possibilities that overvoltage or undervoltage could occur from sudden changes in PV output. Voltage deviations at regulation nodes are important if the utility is concerned with reduced asset life due to potential increase in operations.

Protection issues occur due to increased fault current from distributed energy resources [9,10]. Increased fault currents impact the coordination between fuses and other automatic protection, the visibility for the breaker to determine remote network faults, as well as sympathetic breaker operation. Protection issues are ultimately based on existing settings and how PV impacts those settings, but to generically determine impact across a range of networks, utility-defined thresholds are applied.

Finding Trends

The derivation of the streamlined method began with the results from the detailed hosting capacity study. Trends have been observed with increased penetration levels for each issue on each network. An example of this for maximum primary node voltage is shown in Figure 1. Each marker indicates the maximum network-wide primary voltage in a particular deployment of PV. There is noticeable variation in the magnitude of impact at any specific penetration level. This indicates the impact is not only dependent on the aggregate amount of PV on the network but also on the location of the individual PV systems. A weighted average primary resistance is calculated to characterize the group of PV systems in each PV deployment. The weighted average value (*Ravg*) for a specific deployment is determined as:

$$R_{avg} = \left(\sum_{i=1}^{k} \text{Resistance}_i \cdot \text{PVsize}_i \right) \Big/ \sum_{i=1}^{k} \text{PVsize}_i$$

where *i* defines the individual PV system, *Resistance* is the short circuit resistance to the PV system, *PVsize* is the active power size of the PV system, and *k* is the number of PVs in the deployment. As the feeder becomes saturated with PV (high total penetration due to many customers with PV), the characteristic converges to the load center. At low penetration, there is more diversity in the PV deployment characteristic. In general, trends in similar voltage magnitude appear roughly linear, however, the trend can be linked to the inverse of resistance (1/*Ravg*).

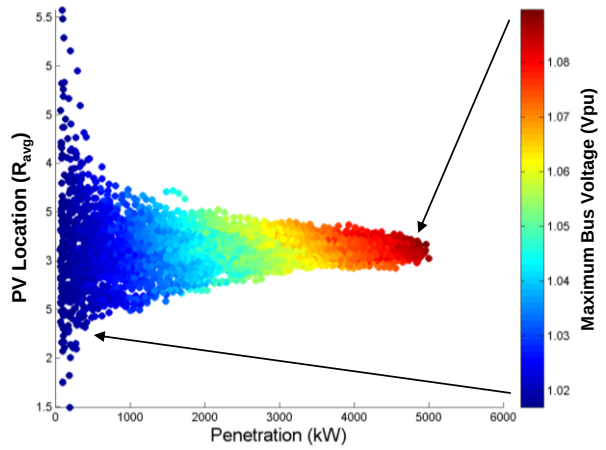

Figure 1. Voltage Magnitude and PV Deployment

Hosting Capacity Assessment across Multiple Networks

The detailed hosting capacity assessment examined the impact and trends to all issues on multiple networks. The residential/commercial PV hosting capacity for a subset of networks analyzed to date is shown in Figure 2. Each colored region represents no issues (green), issues dependent upon PV location (yellow), and issues regardless of PV location (red). Minimum hosting capacity (when issues potentially begin to occur) is defined by transition from green to yellow region. Maximum hosting capacity (when issues begin to occur regardless of individual PV location) is defined by transition from yellow to red region.

One observation that is readily ascertained is that there is a considerable range in the amount of PV that can be accommodated across all networks without taking preventative measures. This is due to the network's hosting capacity dependency on all network and PV characteristics. A single characteristic is not capable of accurately determining a network's hosting capacity. This is why a streamlined approach is necessary over any simple screening method that is based on limited information (e.g, load level only). In the streamlined approach, because it is model-based, all network characteristics and responses are included when determining the potential PV impact.

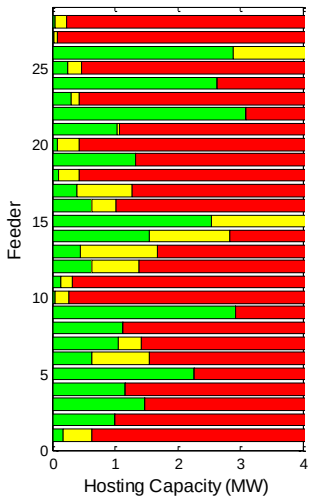

Figure 2. Network Hosting Capacity

STREAMLINED METHODOLOGY

The streamlined method used in the analysis of hosting capacity is complex. To best describe the methodology, a generic illustration is provided. The illustration is provided specifically for small-scale residential/commercial PV. Similar illustrations could be derived for large-scale PV.

Four possible deployments of small-scale PV across the network are show in Figure 3a. Three deployment distributions have 1.5 MW total penetration but with unique locations of PV centered near the network-head, mid-network, and near the network-end. The fourth distribution has a similar location of PV, centered mid-network, but only 0.5 MW total penetration. The current distribution from these PV deployments are shown in Figure 3b. The current distribution would be the aggregate PV current flowing out of the network if all loads are offline. The total penetration and location of PV cause varying impact to the network as illustrated in Figure 3c. Higher penetration increases the impact as well as PV located near the network-end.

For the three locations of PV on the network, the penetration can be increased until the network impact exceeds utility-defined thresholds. When this occurs, the hosting capacity is found for the particular location of PV. The variation in hosting capacity for this example is shown in Figure 3d.

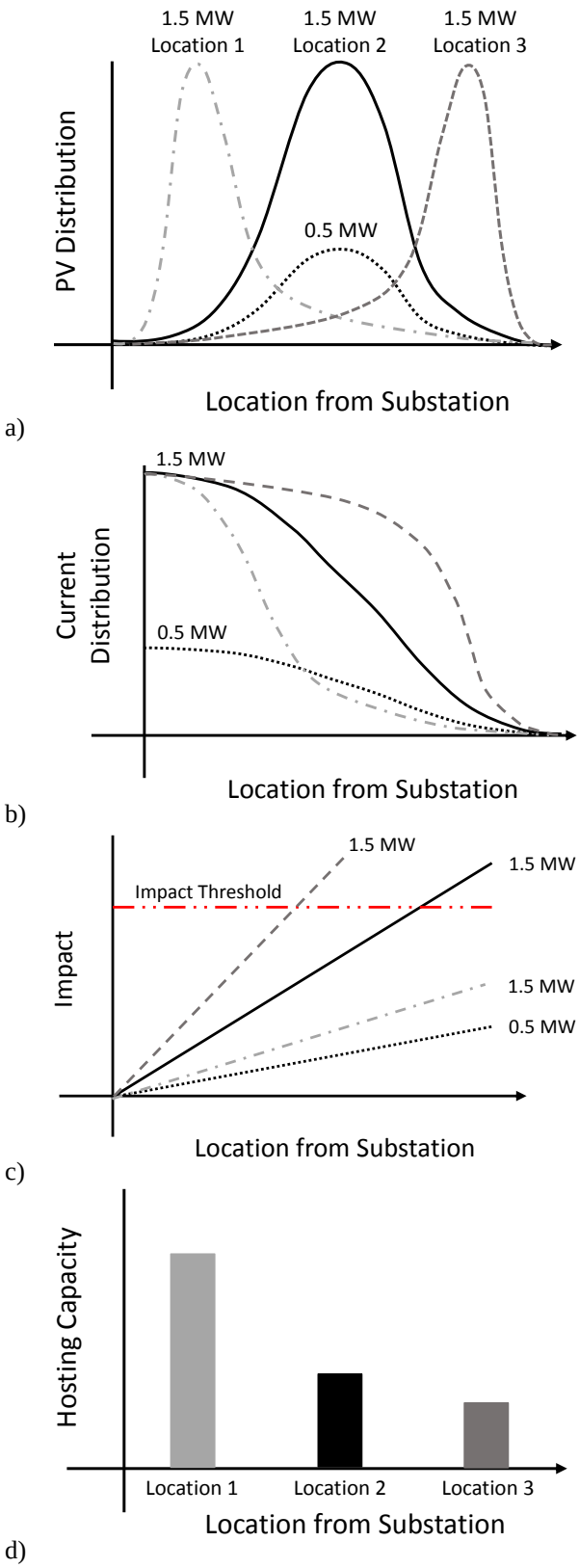

Figure 3. Example of Streamlined Method a) PV Distribution b) Current Distribution c) Impact d) Hosting Capacity

The streamlined method can determine hosting capacity irrespective of actual customer size/location on the network (shown by the solid line in Figure 4), but customer-based hosting capacity will be constrained by the actual size and location of those customers. The extreme boundary of possible characteristics of aggregate PV deployments on the network are shown in the figure as well. These extreme boundaries would only occur due to clusters of PV near the network-head or near the network-end. This boundary establishes the conservative hosting capacity range based on the two intersections of the Hosting Capacity curve and the Extreme Boundary (the hosting capacity range is discussed in Figure 2).

Diversity from branches on the network can increase the network hosting capacity. The network could have several branches along the primary. These parallel branches can effectively reduce the overall network impact. Based on the number of parallel branches and where they occur, the effective impedance can be calculated. Diversity typically increases to mid-network and decreases afterward. This will provide an optimistic hosting capacity range as shown in Figure 4 based on the two intersections of the Hosting Capacity with Diversity curve and the Extreme Boundary. There are additional factors of diversity discussed in [4].

The realistic hosting capacity range, however, must consider more moderate and likely bounds for aggregate PV characteristics as shown in Figure 4. These moderate bounds have been identified from EPRI's detailed analysis where customers on the network more randomly attain PV. Only at very low penetration levels is there a wide variation in the PV distribution characteristic location (*Ravg*). As penetration increases and more customers acquire PV systems, the characteristic of the PV deployment location converges to the characteristic of the load distribution (load center) on the network (similarly shown in Figure 1). The realistic maximum hosting capacity includes diversity while minimum hosting capacity does not.

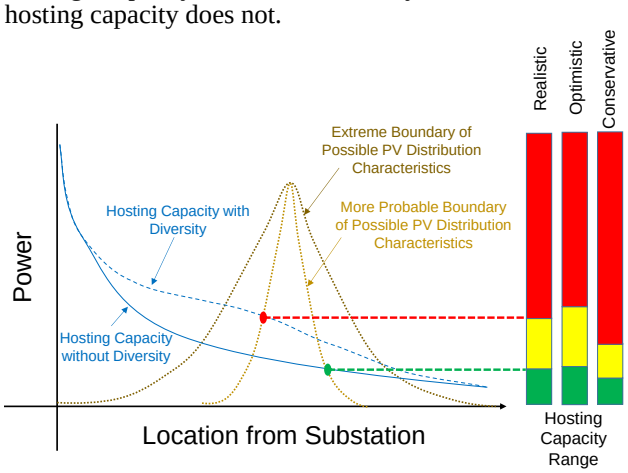

Figure 4. Range in Streamlined Hosting Capacity

The streamlined analysis can provide a conservative, optimistic, and realistic estimate of the range in network hosting capacity. The realistic range in hosting capacity is used for the streamlined hosting capacity validation to detailed hosting capacity results in the next section.

RESULTS

The hosting capacity results from the streamlined approach are compared to those from the detailed study to verify the method's effectiveness. The streamlined hosting capacity can provide more/less conservative results based on users' input and interpretation. To validate to the detailed hosting capacity results, however, the streamlined method must take into consideration a similar level of diversity and PV locational bounds.

How to Interpret Hosting Capacity Results

The streamlined small-scale PV hosting capacity results for one issue on a utility network is shown in Figure 5. The figure illustrates the network aggregate PV hosting capacity based on electrical location of PV. The solid line indicates the small-scale distributed PV hosting capacity without diversity. The dashed line indicates the small-scale distributed PV hosting capacity with diversity. The dotted lines indicate the upper and lower bound of aggregate PV characteristics simulated in the detailed analysis. The up/down arrows indicate the detailed analysis maximum/minimum hosting capacity, respectively.

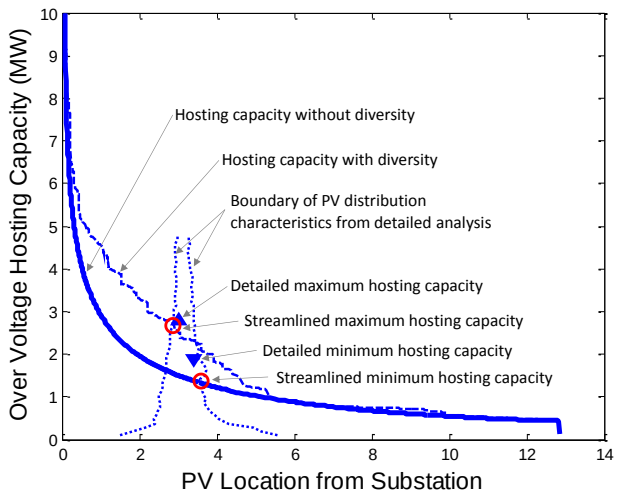

Figure 5. Streamlined and Detailed Hosting Capacity Results for Overvoltage on One Network

To compare streamlined minimum/maximum hosting capacity to the detailed analysis results, diversity must be taken into consideration. For minimum hosting capacity in the detailed analysis, the diversity is likely low but can exist. Therefore the detailed minimum hosting capacity should be near the intersection of the solid and right dotted line (lower right circle) but can be as high as the intersection of the dashed and right dotted line if diversity exists in the detailed analysis PV deployment. For maximum hosting capacity, the full range of diversity is likely included thus the streamlined maximum hosting capacity is best defined as the intersection of the dashed and left dotted line (upper left circle). The actual magnitude of diversity in the detailed analysis PV deployments resulting in the maximum and minimum hosting capacity, however, is not quantified.

The streamlined results are close to the detailed analysis results when diversity and locational bounds are included. The minimum small-scale PV hosting capacity occurs due to less diversity, whereas the maximum small-scale PV hosting capacity occurs due to a greater extent of diversity.

Comparison with Additional Networks

As the detailed analysis progressed over time, trends have been observed and additional outputs have been collected on subsequent networks. These most recent networks have then become the basis for the development and validation of the streamlined method. This subset of networks includes networks of multiple voltage classes from 4 kV to 35 kV. There is also a range in network characteristics such as resistances, voltage control devices, step-down transformers, load levels, load locations, impedances, and many more.

The minimum hosting capacities are shown in the comparison between the streamlined and detailed analyses since the level of diversity is lowest for those PV deployments. For the streamlined minimum hosting capacity, no diversity is assumed. As shown in the previous figure, however, there is likely some diversity in detailed analysis PV deployments which can result in slightly higher detailed hosting capacities. Therefore, the streamlined hosting capacity will typically be slightly more conservative (lower) than detailed analysis results.

Figure 6 shows the comparison of streamlined and detailed minimum primary node overvoltage hosting capacity for small-scale PV. When the detailed hosting capacity exceeds the maximum analyzed penetration of the detailed analysis (based on peak load level), the hosting capacity is set to the maximum analyzed penetration. When this occurs, a hash appears at the top of the columns. The streamlined hosting capacity analysis can also analyze higher penetrations than the detailed analysis, but to provide comparable results, the streamlined analysis results are only analyzed to the maximum level in the detailed analysis. If the streamlined hosting capacity is greater than the maximum analyzed penetration, the streamlined hosting capacity is set to that maximum analyzed penetration.

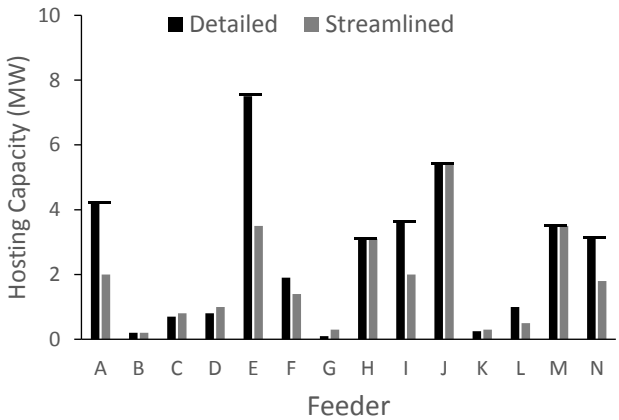

Figure 6. Overvoltage Hosting Capacity Comparison

For many networks, the hosting capacities match nicely. Error is typically introduced when hosting capacity is

higher and thus diversity has a more significant impact. The streamlined method:

- Effectively identifies lower hosting capacity networks
- Has closest match at low hosting capacity
- Has a more conservative result at higher hosting capacity
- Has comparable results for all potential issues [4]
- Is effective for large-scale and small-scale PV [4]

Potential Applications

While the focus of this method is to quantify, on a network-by-network basis, individual hosting capacities and impacts, it is not intended to replace detailed studies. The broader application of this methodology is to expand the scope of analyses to entire systems. While some details are not captured through the streamlined approach, the beneficial applications outweigh the potential loss by allowing system-wide assessments to be performed.

Various applications can be realized through implementation of the streamlined method, particularly those related to assessments across an entire service territory. Several key applications are:

- Determine the existing hosting capacity for each network across the entire distribution system under current grid configurations
- Identify locations that can minimize the upgrades necessary to accommodate PV
- Improve screening techniques that efficiently account for the proposed PV and associated grid capacity at that location
- Improve visibility into substation-level capacity for accommodating PV connected at the individual network level
- Provide better visibility to the specific issues that arise
- Identify locations and aggregate PV for improved bulk system studies
- Streamlined methods repeated in an automated fashion for additional distribution configurations
- System-wide comparison of large-scale PV vs small-rooftop PV in terms of hosting capacity and issues that may arise
- Visual interpretation of optimal verse non-optimal locations for PV (Figure 7)
- Value of solar to the utility
- Networks and locations where smart inverter capabilities are needed can be identified
- Sensitivities regarding location/size can be investigated and system impacts rolled up to system-level

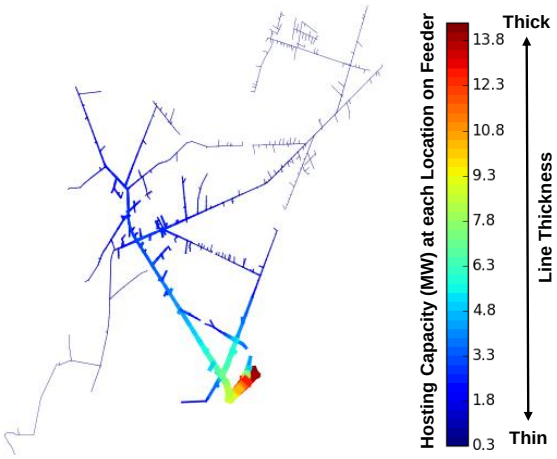

Figure 7. Visual Interpretation of Location Dependent Hosting Capacity

CONCLUSION

The streamlined hosting capacity analysis and methodology provides a fast and effective technique to calculate the distribution system impact from PV. The solution is defined as the amount of aggregate PV that does not cause system impact to exceed utility-defined thresholds. The analysis assigns each network a maximum and minimum hosting capacity. Location-based impact can also be determined within the tool based on provided geographical representation of the locational optimality of PV. Beyond providing a network specific impact analysis, a system-wide impact analysis can also be performed by systematically processing all networks within the system.

The current methodology depicted in this paper is based on PV as the distributed energy resource, unity power factor inverters, and no existing distributed generation. As the methodology evolves, these three additional factors as well as others will be considered. Inclusion of additional issues or the removal of issues may also change when appropriate.

The method and analysis has been developed and validated with Matlab interfacing directly with the distribution software OpenDSS. The method has also been translated with Python interfacing directly with Cyme. This will allow the analysis to be applied directly to utility models and enable the utility to conduct analyses when and as often as necessary, such as for system changes. Several additional benefits of the streamlined analysis over detailed analysis include:

- Simulation time is faster (minutes compared to weeks)
- Considers a wider range in possible PV distributions
- Applies network based limitations and diversity
- Considers utility and residential/commercial class PV
- Scripted to auto analyze a database of networks

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