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Stochastic Approach for Distribution Planning with Distributed Energy Resources

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SUMMARY

High penetrations of distributed energy resources (DER), specifically distributed photovoltaic generation, in the electric grid is beginning to challenge distribution planners and engineers. A stochastic approach for distribution planning is necessary to understand the potential impacts of future levels of DER on distribution operations. The stochastic nature of the analysis captures the unpredictability of 'where' and 'how much' DER can eventually be installed on a feeder. The analysis illustrates DER impact on voltage, protection, harmonics, demand response, and control while considering total penetration levels as well as localized constraints and concentrations.

In this paper, an analysis approach is presented that can be applied to determine feeder-specific solar photovoltaic hosting capacity. The variables that influence hosting capacity are explained and an example with relevance to over-voltage limits is provided.

KEYWORDS

Distributed Energy Resources, Distribution Planning, Photovoltaics, Voltage

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I. INTRODUCTION

Stochastic analyses are necessary to better understand future distributed energy resource (DER) impacts to distribution feeders. Single point-of-interconnect studies are only as accurate as the DER actually being modeled at that time. The unpredictability in the size and location of future DER, specifically distributed solar photovoltaic (PV) generation, therefore, justifies the large set of potential photovoltaic scenarios when examining impact to the feeder. The stochastic nature also allows incorporation of various PV class sizes such as large-scale units directly connected to the primary through a dedicated step-up transformer or small-scale units connected at the customer secondary.

The stochastic analyses should address distribution planning issues including voltage, thermal loading, protection, harmonics, and control. How a feeder responds to PV generation is unique to the individual feeder's characteristics. The base feeder characteristics include voltage level, load, feeder topology, power delivery elements, power control elements, and control operating criteria.

Although feeder characteristics are a key factor in the circuit response from distributed PV [1], additional factors include the PV size, location, and variability in output [2]. The distribution connected PV will ultimately mold the overall feeder response. The specific feeder impact(s) will determine the appropriate PV penetration limits/hosting capacity [3,4] applied to the feeder.

In this paper a stochastic analysis approach is described that can be used to determine feeder photovoltaic hosting capacity.

II. DISTRIBUTED PV MODELING AND ANALYSIS APPROACH

This section summarizes the modeling and analysis approach used by EPRI to evaluate distributed PV impacts on the electrical system. The analysis incorporates PV systems with the 'base' electrical model of the distribution feeders. Small-scale residential, commercial, and large-scale (MW) PV systems are considered in the analysis. Distribution system impacts are characterized and quantified through the model's response to specific and randomly generated PV deployment scenarios.

A. Base Feeder Model

The three-phase base electrical feeder model used in the analysis consists of all primary and secondary power delivery elements from the substation transformer to the individual customer. Control elements such as capacitors and regulators are included with fully implemented control algorithms. Loads are based on SCADA or AMI measurements, and depending on the location of measurements, load is allocated to each individual customer.

The detail of the model must include all feeder components down to the individual customer level due to small-scale photovoltaics connected at the individual customer service points. Lumping load, photovoltaics, or neglecting service impedance could potentially obfuscate the feeder impact.

B. Distributed PV Systems

A key component in accurately assessing distributed PV impacts on the distribution system is accurately representing the nature of the PV systems themselves. This includes not only sufficiently accounting for the electrical characteristics of the distributed generation, but also the array size and solar irradiance which inherently drives the PV output. The method for modeling the actual PV system itself is described in further detail in [5,6].

In order to reasonably represent the affect of large and small scale PV, the analysis is split into the two deployment routines: Small-Scale PV and Large-Scale PV.

Each deployment routine serves as a tool for examining system response from a different conditional perspective. Results from the separate deployment routines can be used to provide a complete picture concerning the nature and relationship between PV generation and system impacts.

Small-Scale PV deployment uses the customer service as the most probable point of coupling for each individual PV. The adoption rate at these customer locations are weighted based on their likelihood of PV adoption. Some areas on a feeder can have a higher rate of adoption based on factors such as socioeconomics.

The customer class is used to distinguish between using a residential or commercial PV distribution for randomly selecting installed PV size. These distributions are derived from the

California Solar Initiative Survey [7]. In the analysis, the maximum PV size is restricted by the customer peak load and size of the service transformer. The peak loading of the individual customers is used as a metric to gauge 'likely' maximum PV size.

The random allocation of PV is performed for each scenario and penetration level as shown in Figure 1. As penetration increases for a specific scenario, further PVs deployed are in addition to those existing in the same scenario at the previous penetration level. Penetration is increased until all customer locations have been deployed with PV. Distributed PV systems that exist in the circuit prior to the analysis can be included in each scenario. Each scenario is unique in the order that PVs are deployed.

Large-Scale PV deployment uses a select number of three-phase primary line locations as probable points of interconnection. These locations can have a higher likelihood of adoption such as that described for Small-Scale PV. At each penetration level, one 500 kW PV system is interconnected at a randomly selected location behind a three-phase step-up transformer. Additional 500 kW systems are added to the model until the maximum considered threshold has been deployed. Again, each penetration level builds upon the previous penetration level for a given scenario.

A sweep of Large-Scale PV is also conducted by deploying a 1 MW PV system at every three-phase primary bus behind the step-up transformer. The PV is swept through the circuit to determine potential isolated locations that would violate circuit monitoring criteria.

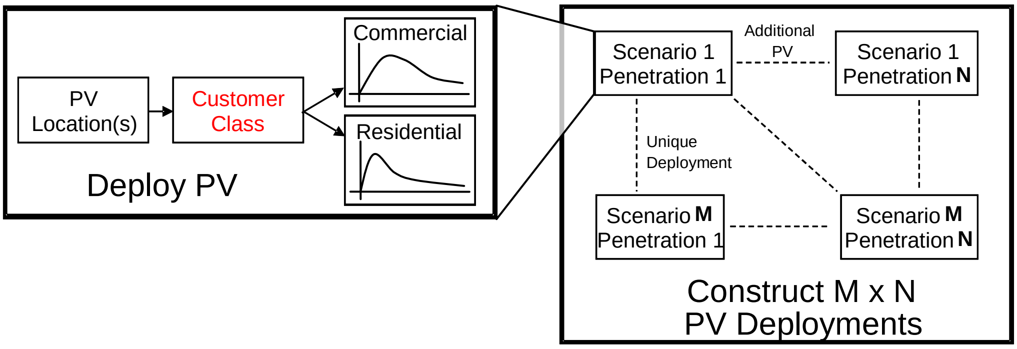


Figure 1. Small-Scale PV Deployment

C. Stochastic Analysis Framework

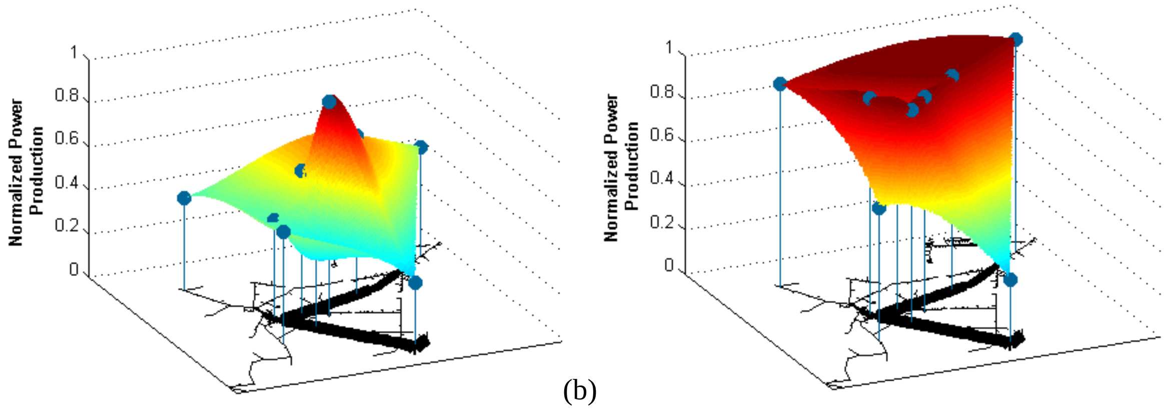
The PV impact analysis is examined in two parts. The first part is a steady-state analysis that examines a large set of both Large-Scale and Small-Scale PV deployment scenarios and calculates impact on voltage, loading, protection, and harmonics. The second part of the analysis is a verification of steady-state results using a time-series (quasi-dynamic) analysis. The time-series analysis determines a more 'realistic' circuit response that would occur based on measured load and solar irradiance data.

The steady-state voltage analysis determines the 'worst case' voltage response that would occur for the sudden change from zero to full PV output. This is not considered a typical response in output of PV; however, the simulated impact to the grid can occur because the solar ramping capability can be quicker than time delays on typical regulation equipment. This yields the feeder response due to cloud shading just prior to regulating equipment operation. There are four base load levels simulated that include: absolute maximum, absolute minimum, solar peak maximum, and solar peak minimum. The absolute maximum and minimum loads are used to derive a bounding envelope for the response. The solar peak maximum and minimum loads determine more probable bounds for the circuit response. These solar load levels occur when PV is near peak output.

The analysis also determines the 'worst case' protection impacts for all sectionalizing devices. This is examined due to various fault types at all sectionalizing device locations. Additionally, the analysis determines the 'worst case' harmonic impacts due to system resonance at both absolute maximum and minimum loading.

The time-series analysis is conducted for load/PV time-of-day coincident scenarios. The load and PV are to resemble scenarios from the steady-state analysis. One day of time dependent load is chosen for the maximum load and one day for the minimum load. Each day is examined with highly variable and non-variable high resolution (one second) solar irradiance data [8,9]. High resolution irradiance is necessary to capture impact on regulation equipment.

Figure 3 (a) shows an example of a feeder with the geographic dependent normalized power production for a snapshot in time derived from eight field monitors using interpolation between points (floating mesh). The field monitors are shown by vertical lines to circuit location. Figure 3 (b) shows the normalized power production over the feeder only 26 seconds later can change considerably.



(a) (b)

Figure 3. Space-Time Normalized Power Production at a) time=0 sec and b) time=26 sec

III. CIRCUIT MONITORING CRITERIA

Distributed generation planning criteria and limits have been identified by both North American and European practices [10]. Table 1 shows a summary of criteria used to determine PV hosting capacity limits. The threshold of impact that is used for each criterion to determine the hosting capacity is not necessarily standard planning limits. Some feeders operate with more restrictive limits than others, while some criterions are not regulated by any set standards.

Table 1. Circuit Monitoring Criteria

Voltage	Protection	Harmonics	Thermal Loading	Control
Overvoltage	Additional Current Contribution	Total Harmonic Distortion	Overloads	Load Tap Changers
Deviation	Anti-Islanding	Individual Harmonics	Masking	Regulators
Imbalance	Sympathetic Tripping		Consumption	Capacitors
	Fuse Coordination		Losses	
	Reduction of Reach			

Voltage impact is examined separately for primary, secondary, capacitor, and regulator nodes. The monitoring criterion applied includes overvoltage, voltage deviation, and voltage imbalance. The overvoltage and deviation thresholds are adjusted for distribution capacitor and regulator nodes to account for potential control actions.

The chief means of fault detection on utility distribution systems is series overcurrent relaying. The presence of PV systems has the potential to disrupt the coordination of the series overcurrent devices by essentially turning the radial system into a meshed network system. The fault current contribution from the PV systems is used to judge whether a single or aggregation of PV will interfere with the detection and clearing of faults [10,11]. This allows computation of sympathetic breaker tripping, breaker reduction of reach, breaker/fuse coordination, and anti-islanding issues.

A distortion analysis is performed for PV deployments with all possible capacitor configurations. The distortion analysis identifies if the inverter harmonics, background load harmonics, and system resonance impact system voltage distortion.

Thermal loading limits are an important factor that can restrict the hosting capacity of PV on a given feeder. Typically, the deployment of PV reduces the net forward flow on the system; however, PV systems can potentially cause a greater reverse flow on the circuit at low load conditions. The reduced forward flow is enough to raise concern over demand masking. In the analysis, demand masking is examined by correlating measured solar irradiance data with measured feeder load. Change in net demand will also affect feeder losses and consumption.

Control limits are analyzed in the time-series analysis. Photovoltaic deployments that show likely issues are simulated while counting increased duty on regulation equipment. An increase in regulator or capacitor operations is considered to ultimately decrease device life.

IV. HOSTING CAPACITY EXAMPLE

The example results in this section are for a 12.5 kV class utility feeder with an approximate 6 MW peak load. The feeder encompasses a 35 mi^2 footprint and has three sets of line regulators in addition to the substation load tap changer. The photovoltaic hosting capacity results based on over-voltage criteria are presented.

The maximum primary feeder voltage for each of 5000 Small-Scale PV deployments during peak load is shown in Figure 4. The maximum feeder voltage rises as PV penetration increases. The cause of overvoltage violations can be attributed to the size and location of the individual PV systems. The aggregate PV impedance characteristic is determined by the weighted average short circuit impedance to each PV system. Overvoltages are more likely to occur at lower penetrations if this characteristic impedance is high. As penetration increases, the overvoltages occur with lower characteristic impedances.

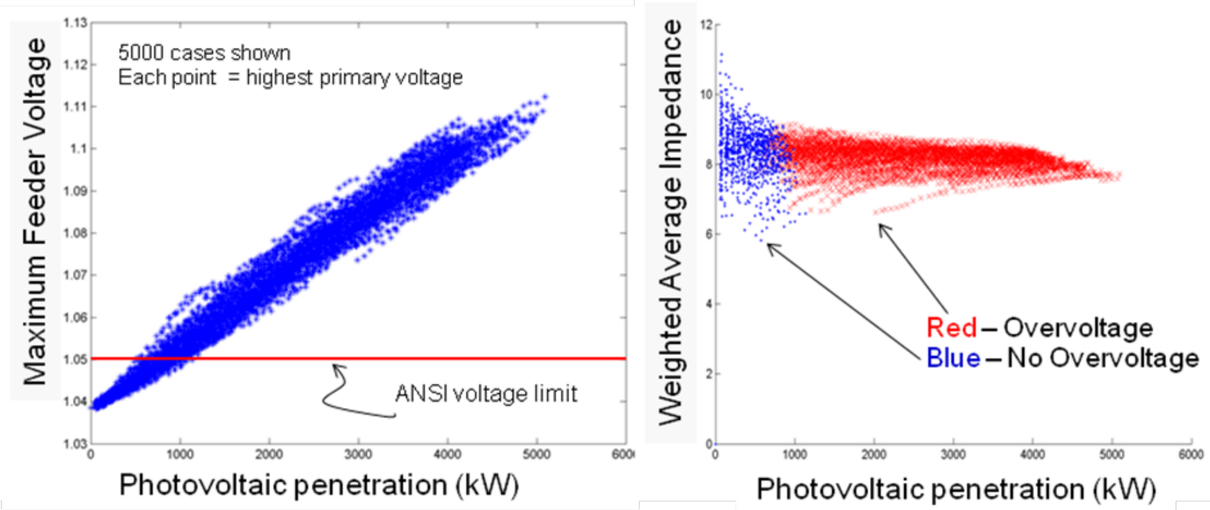


Figure 4. Maximum Feeder Voltages and PV System/Impedance Characteristics for Small-Scale PV at Maximum Load

Due to variation in PV size and location at any one particular penetration level, the maximum feeder voltage can vary. For example, at 1 MW total PV, the maximum feeder voltage could be anywhere from 1.048 to 1.063 Vpu. Similarly, the point at which a PV deployment causes the maximum voltage to exceed the ANSI voltage limit varies from 540 kW to 1173 kW. At 540 kW overvoltages only occur for the particular PV deployment. This deployment identifies the feeder minimum hosting capacity (minimum amount of PV that can be added to feeder to cause unacceptable overvoltages). As PV penetration increases further, more PV deployments are likely to also cause overvoltages. For all PV deployments at or above 1173 kW total PV, overvoltages occur in the simulation. This deployment identifies the feeder maximum hosting capacity (total amount of PV that causes unacceptable overvoltages regardless of individual PV size/location).The minimum and maximum hosting capacity is caused by the most non-optimal and most optimal PV deployments, respectively. The likely PV deployment will be neither and thus the hosting capacity will be somewhere in-between.

Hosting capacity is dependent on PV size/location, load, and circuit criteria. Some criteria such as overvoltage may have lower thresholds than the ANSI limit like in the case of planned conservation voltage reduction. The hosting capacity is also dependent on load level. Over-voltage based hosting capacity limits are shown in Table 2 for four load levels. The solar peak minimum load PV penetration limits are the same as absolute minimum load due to absolute minimum load being coincident with peak solar output.

Solar minimum or solar maximum load hosting capacity limits may be more realistic if absolute maximum and absolute minimum load is not likely to coincide with solar peak output. The median hosting capacity represents when 50% of the stochastic PV deployments cause a violation. Thus, the hosting capacity for overvoltage criteria is 421 kW (7% of peak load) when applying conservative conditions, while the hosting capacity based on typical load and a 'normal' PV deployment would suggest 630 kW (11%).

Table 2. Small-Scale PV Voltage Based Feeder Hosting Capacity

		Hosting Capacity (kW)			
		Max Load	Solar Max Load	Solar Min Load	Min Load
Primary Over Voltage	Minimum	540	541	421	421
	Median	871	782	630	630
	Maximum	1173	1073	977	977

V. CONCLUSIONS

Distributed PV can have an impact on feeder voltage, protection, harmonics, loading, and control. Studies performed prior to PV feeder adoption are necessary to identify these impacts, and are determined best through a stochastic analysis of distributed photovoltaics. Long term studies are not able to take advantage of known adoption locations and must thoroughly exhaust potential adoption scenarios.

The detailed analysis allows a specific feeder hosting capacity to be determined based on multiple feeder response criteria. The level of hosting capacity is also dependent on the individual feeder's threshold to response. Not all responses have a defined threshold such as the ANSI voltage limit. For some utilities, and also specific feeders, those limits are held to tighter restrictions. This is the case with feeders controlled for conservation voltage reduction.

Response limits and photovoltaic hosting capacity are specific for individual feeders. The hosting capacity is best applied based on individual feeder response. Broad assumptions for feeder photovoltaic hosting capacity should be applied carefully as feeder characteristics such as feeder impedance and regulation can be more influential than characteristics such as load and voltage class.

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