PV Interconnection Risk Analysis through Distribution System Impact Signatures and Feeder Zones

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***Abstract*— High penetrations of PV on the distribution system can impact the operation of the grid and may require interconnection studies to prevent reliability problems. In order to improve the interconnection study process, the use of feeder zones and PV impact signatures are proposed to group feeders by allowable PV size as well as by their limiting factors for the interconnection. The feeder signature separates feeders into different impact regions with varying levels of PV interconnection risk, accounting for impact mitigation strategies and associated costs. This locational information improves the speed and accuracy of the interconnection screening process. The interconnection risk analysis methodology is based on the feeder and interconnection parameters such as: feeder type, feeder characteristics, and location and size of PV. PV impact signatures, hosting capacity, and feeder risk zones are demonstrated for four realistic distribution systems.**

***Index Terms* – distributed power generation, photovoltaic systems, power distribution, power system interconnection**

I. INTRODUCTION

Conventionally, distribution systems have been designed for voltage regulation and protection coordination considering one-way power flowing radially from the substation to the customers. Adding large amounts of distributed generation may cause two-way power flow changing this historic paradigm and possibly impacting other customers on the distribution feeder. Rooftop photovoltaic (PV) generation is one of the most common forms of distributed generation, and the variability and intermittency of solar power increase the challenges to grid operation. Two common concerns of the interconnection of these systems are steady-state over-voltage and line-loading violations [1]. PV can also cause issues with voltage regulation equipment [2], system losses [3], harmonics [4], voltage flicker [5], and protection [6].

Therefore, before interconnections are approved by utilities, they must go through a screening process to determine if the impact risk justifies requiring an interconnection impact study to thoroughly investigate the potential adverse effects of an interconnection [7]. Currently, such impact studies can be time consuming and expensive, a problem that is only worsened by increasing penetration levels. With increasing numbers of these installations, it is becoming increasingly important for utilities to quickly assess and screen for potential interconnection risks of PV systems.

While PV interconnection impact studies investigate a specific location and PV size, another approach is to analyze the entire feeder and determine the feeder's PV hosting capacity. The results are feeder specific, but they are general to any interconnection location. Using this approach, if the total installed PV on the feeder is less than the hosting capacity, regardless of location, there will be no significant impact to the grid operations. EPRI has performed significant research in the area of feeder hosting capacity for PV [8], [9]. While their research was focused on determining a single value for the hosting capacity for the entire feeder, our research expands on their approach to investigate all the regions of the feeder that may allow many different hosting capacity values. Work has also been done to show how hosting capacity is a factor of the distribution parameters and how hosting capacity can be increased with PV inverter reactive power control strategies [10], [11].

Because hosting capacity and interconnection studies are generally specific to a given feeder topology, load level, or other feeder characteristics, the ability to interpret the results for a specific bus or feeder in a manner that generalizes this information for analysis is of interest. The contribution of this paper is the analysis of hosting capacity simulation results to obtain a feeder impact signature for PV interconnections that more precisely determines the local maximum hosting capacity of individual areas of the feeder. The feeder signature provides improved interconnection screening with certain zones that show the risk of impact to the distribution feeder from PV interconnections. These zone maps can be used for interconnection request screening in a more accurate way that accounts for the feeder characteristics and interconnection location specific information.

The work in this paper contributes to the overall objectives of developing a Feeder Impact Risk Score Technique (FIRST), which seeks to quantify the risk level of interconnection requests by comparing and matching feeders to clusters of known prototypical feeder topologies and characteristics. The category of feeders will display similar interconnection risks, limiting factors, interconnection zones, and optimal mitigation strategies, thus improving the speed and accuracy of the interconnection screening process. By performing thorough PV interconnection simulations on several feeders, the most critical characteristics that cause adverse impacts can be collected and analyzed for general feeder behavior and universal applicability.

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II. FEEDERS ANALYZED

The analysis is demonstrated for four distribution feeders. These feeders represent a range of possible topologies and characteristics, which result in very different feeder impact signatures. The topology and locations of major circuit elements are shown in Fig. 1A through Fig. 1D, and relevant feeder details are listed in the table in Fig. 1E. The four feeders being used are referred to as Ckt5, Ckt7, J1, and ML3. Ckt5 and Ckt7 are publically available as example feeders in OpenDSS [12].

III. ANALYSIS METHODOLOGY

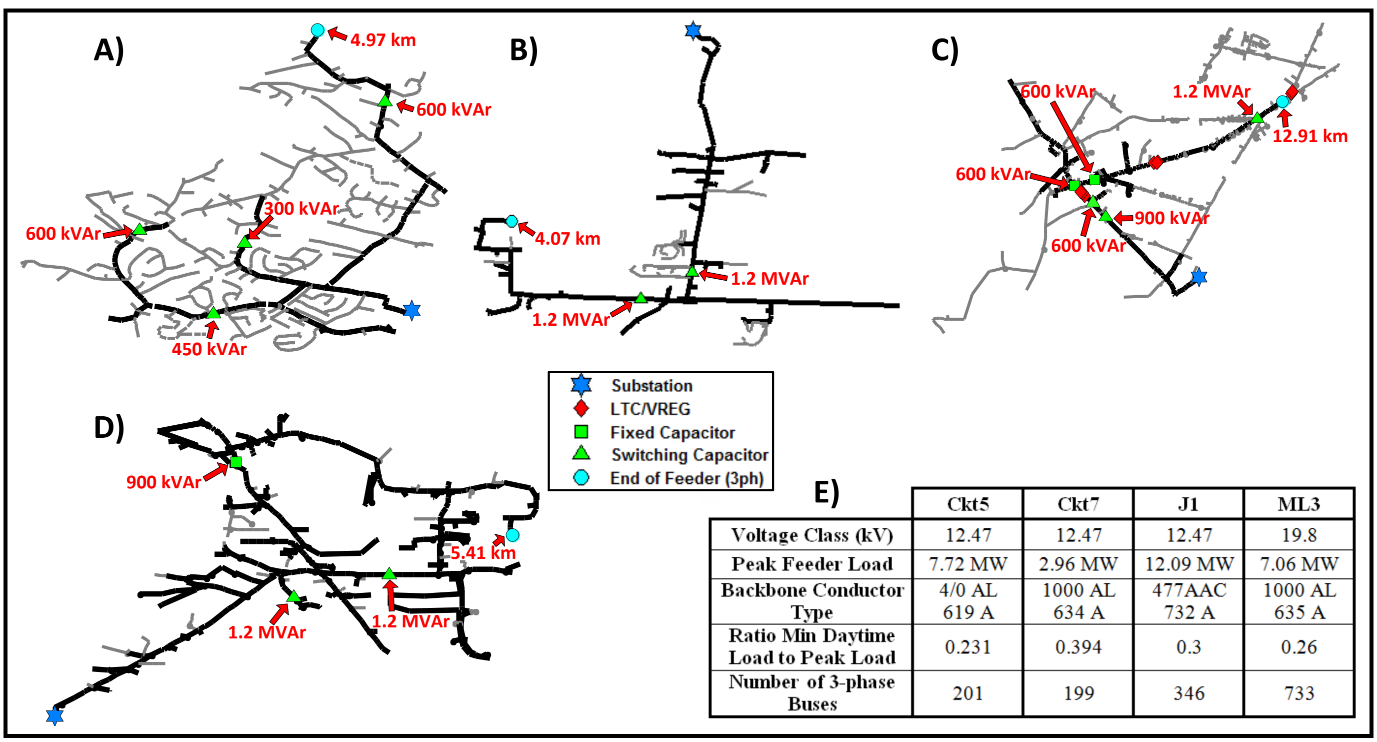
The analysis is performed in OpenDSS, an open-source three-phase distribution system simulation software developed by EPRI [12]. OpenDSS is controlled through the COM interface by MATLAB using the GridPV toolbox [13]. MATLAB is used for creating and iterating through each PV scenario as well as for the analysis of the results. OpenDSS is used to solve the power flow for each case.

We investigate the impacts of large central PV plants on the distribution system by simulating a range of scenarios, each representing a single PV system of a certain size at a single interconnection location. Initially, fixed power factor PV systems producing only real power are considered as they are most common [14], but future work will consider active voltage control [15]. The analysis iterates through possible interconnection locations, sweeping through a range of PV sizes up to 10MW at each location. The number of potential interconnection locations on 3-phase buses varies between feeders, shown in the table in Fig. 1E. The total number of scenarios considered is a function of the total number of PCC locations multiplied by the total number of PV system sizes.

For each scenario, the algorithm solves the power flow and checks for any violations on the feeder. The fundamental procedure of the PV analysis is described in [16]. However, the discussion in [16] is focused on simulating impacts at a specific feeder load level. To improve on this and completely characterize PV impact for a feeder, the simulation of PV must include the full range of load levels of the feeder. Therefore, for each scenario (i.e. each specific PV size and PCC combination) we consider both the maximum and minimum daytime load, where daytime is defined as being between 10am and 2pm [17]. Any feeder violations that were observed at either of those load levels are flagged for the scenario at which it occurred. By considering feeder load in this manner, we effectively remove it as an independent variable, allowing a more comprehensive look at developing a feeder signature. This doubles the number of power flows being examined.

The previous method in [16] was also modified to model PV ramp rates. Solar irradiance variability can quickly change the PV power output. To account for this, simulation of each PV scenario includes extreme ramp rates, both up and down, proportional to the PV plant size [18]. Altogether, three separate PV ramping cases are considered: up ramp, down ramp, and no ramp (i.e. steady-state). For the up and down ramp cases, it is assumed the ramping is occurring more quickly than the voltage regulation can act. With this added simulation effort, we have effectively tripled the number of power flows being considered.

Another consideration of our algorithm is that of voltage regulation. For the steady-state cases in each scenario, voltage regulation is allowed to act. However, because voltage regulation can act within a band of acceptable states, this adds another level of complexity. In order to more comprehensively investigate the effects of voltage regulation,



	Ckt5	Ckt7	J1	ML3
Voltage Class (kV)	12.47	12.47	12.47	19.8
Peak Feeder Load	7.72 MW	2.96 MW	12.09 MW	7.06 MW
Backbone Conductor Type	4/0 AL 619 A	1000 AL 634 A	477AAC 732 A	1000 AL 635 A
Ratio Min Daytime Load to Peak Load	0.231	0.394	0.3	0.26
Number of 3-phase Buses	201	199	346	733

Fig. 1. Information for four example distribution feeders: A) Ckt5 topology, B) Ckt7 topology, C) J1 topology, D) ML3 topology, and E) feeder characteristics.

we consider two extreme cases: (1) the case in which all voltage regulation is forcing voltage toward the top of the acceptable band and (2) the case in which all voltage regulation is forcing voltage toward the bottom of the acceptable band. The former case exhibits the minimal amount of possible headroom while the latter case demonstrates the maximal amount. Considering each of these cases doubles the number of examined power flows.

All voltages in the system are compared to the ANSI C84.1 standard [19], with the distinction of voltage ranges below and above 600 V. When checking a PV scenario for violations in the steady-state, we use ANSI Range A because the voltage regulation equipment has acted and any violations would likely persist over the ANSI 10-minute voltage average. Conversely, the PV ramping scenarios are temporary voltage violations (i.e. much shorter than 10 minutes), which happen before corrective action can be taken by voltage regulation due to their delay. Therefore, a more lenient threshold of 127 V is applied for these infrequent and limited periods of extreme voltages. This is still a more conservative threshold for evaluating fluctuations than the current ITIC curve [20].

After iterating through all of the scenarios, the data and violations of each scenario are stored. The extensive analysis results allow for thorough feeder impact assessments. Details of the problematic scenarios give insight to the most important feeder and PV characteristics that result in violations. This allows for a more technically customized approach than current screening methods.

IV. RESULTS

After performing the analysis of hundreds of thousands of PV scenarios for each of the four feeders, the results can begin to be classified by how often a given PV size is permissible at different locations around the feeder. The figures below (Fig. 3 - Fig. 6) also classify the violations into either voltage or thermal violations. For any given PV size and interconnection location, if the scenario can possibly create a voltage or thermal issue at any daytime load level or PV ramp rate, the scenario is classified as a violation. The best way to analyze the figures is to look at individual vertical slices in the graph. For example, for the vertical profile of a 5 MW PV interconnection on Ckt7, 11% of the possible interconnection buses are in Region E, 55% are in Region D, and 34% are in Region B.

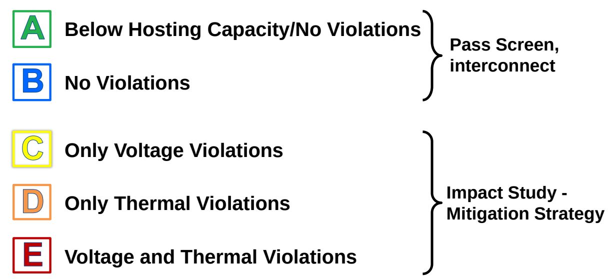


Fig. 2. Feeder regions legend.

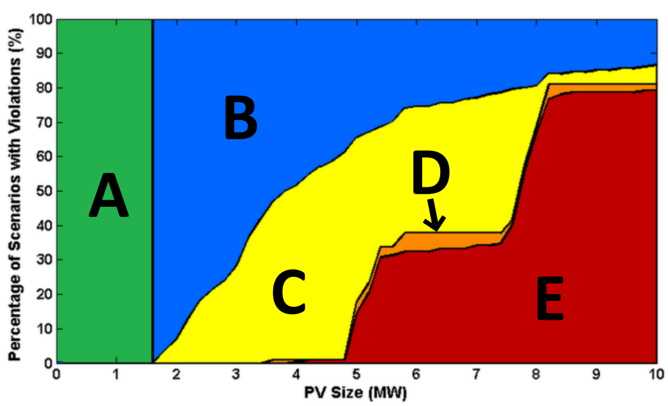


Fig. 3. Ckt5 feeder signature regions.

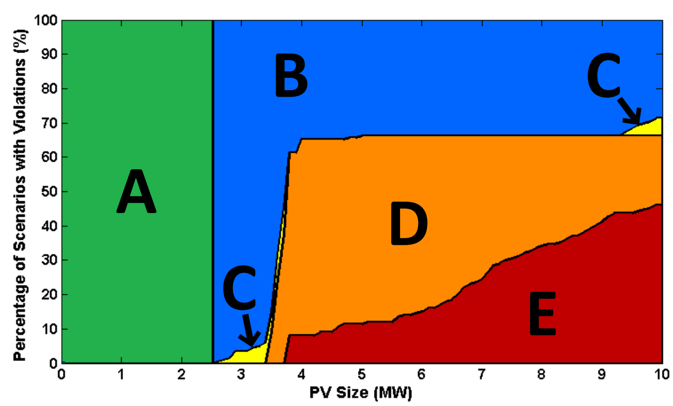


Fig. 4. Ckt7 feeder signature regions.

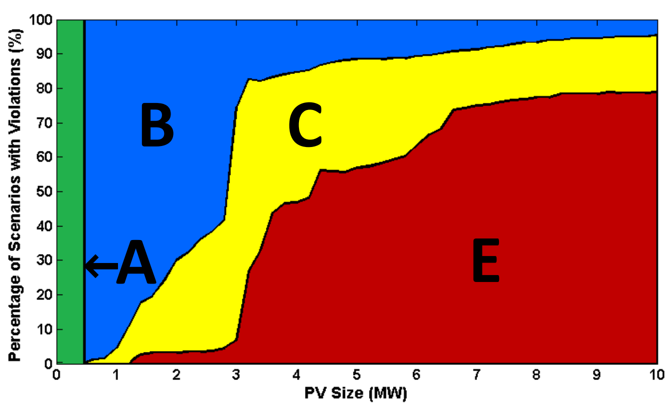


Fig. 5. J1 feeder signature regions.

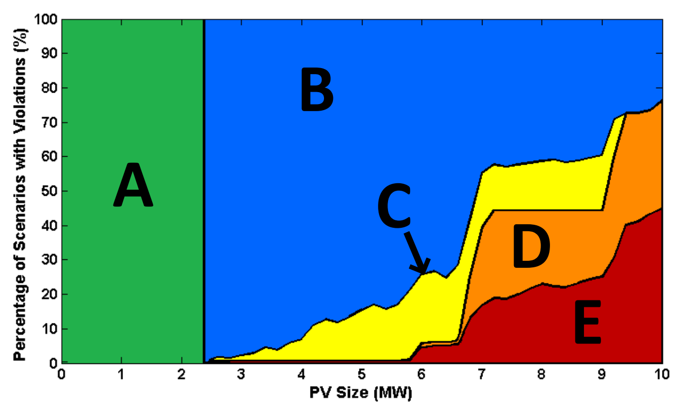


Fig. 6. ML3 feeder signature regions.

Region A and Region B both contain allowed interconnection locations that have no violations. Region A is the area that would be found using a total feeder hosting capacity approach that would give one number for the maximum allowed PV anywhere on the feeder. The feeder hosting capacities, i.e. the boundary between Region A and Region B, are shown for each feeder in Table I. Region A includes the PV sizes below which a system could be interconnected anywhere on the feeder without further investigation.

The other regions refer to system sizes that require further consideration before determining the feasibility of a PV system. Region B contains interconnections that are ultimately allowed but must use some locational details such as PCC distance to the substation and/or conductor type before making this assessment. Regions C, D, and E all include interconnections that have at least one violation and therefore cannot be connected given the current state of the feeder without some mitigation. Regions C, D, and E contain interconnections that respectively result in either only voltage violations, only thermal violations, or both voltage and thermal violations. The legend for the regions is shown in Fig. 2.

The feeder signatures (Fig. 3 – Fig. 6) show the differences between the feeders in the defining factors for their areas of risk. Ckt7 is almost entirely defined by line thermal limits, which makes this 3.5MW threshold a costly barrier to surpass. Ckt5's hosting capacity, on the other hand, is completely defined by over-voltage violations. The barrier present around 1.6 MW is easily increased to 3.5+ MW by altering LTC set-points. Feeder ML3, in contrast to the other two, is a combination of only voltage limits and only line thermal limits.

TABLE I. PERCENT OF PV INTERCONNECTION SCENARIOS IN EACH REGION

	Ckt5	Ckt7	J1	ML3
15% Screen	1.1 MW	0.5 MW	1.8 MW	1.0 MW
Hosting Capacity	1.6 MW	2.5 MW	0.4 MW	2.4 MW
Region A	16.0 %	25.0 %	4.0 %	24.0 %
Region B	31.6 %	32.0 %	26.1 %	49.5 %
Region C	23.7 %	0.7 %	23.3 %	8.4 %
Region D	1.7 %	26.5 %	0.1 %	8.5 %
Region E	27.0 %	15.8 %	46.5 %	9.6 %

V. ADVANCED INTERCONNECTION SCREENING CRITERIA

Looking at Table I, there is significant possible improvement in the 15% of peak load interconnection screen [17]. For example, the 15% screen would allow quite a few PV scenarios up to 1.8 MW on J1 that would cause issues on the distribution system. In fact, 8% of the cases allowed by the 15% screen for J1 are false-positives. The other argument is the number of PV scenarios that would not cause any violations that the 15% screen does not allow. On average for the four feeders, there are 6.4 times more allowed PV scenarios (Region A + Region B) than are allowed by the 15% screen.

A. *Feeder Interconnection Zone Maps*

The purpose of performing the large number of PV scenario simulations is to begin analyzing patterns of feeder characteristics that can be translated into levels of feeder risk for PV interconnection impacts. As seen in the previous section, there is significant advantage to including interconnection locational information in the screening criteria to allow for interconnections without violations in Region B that are greater than the hosting capacity. In each of the examples, Region B contained the greatest number of cases, indicating that this could be a very beneficial realm to exploit. Simple parameters such as distance to the substation and conductor type can allow a distribution feeder to be classified into interconnection zones. For example, the hosting capacity of Ckt5 is 1.6 MW, but the locational hosting capacity of specific points on the feeder is much higher. In Fig. 7, the feeder interconnection zone map for a 6 MW interconnection on Ckt5 shows that there are 25% of the buses that are capable of handling such a system. The feeder zone maps also improve interconnection screening through showing the risk associated with the interconnection. At 6 MW, half the buses with interconnection issues are only caused by voltage violations that may be easily fixed by changing voltage regulation equipment settings or adjusting the power factor on the PV inverter.

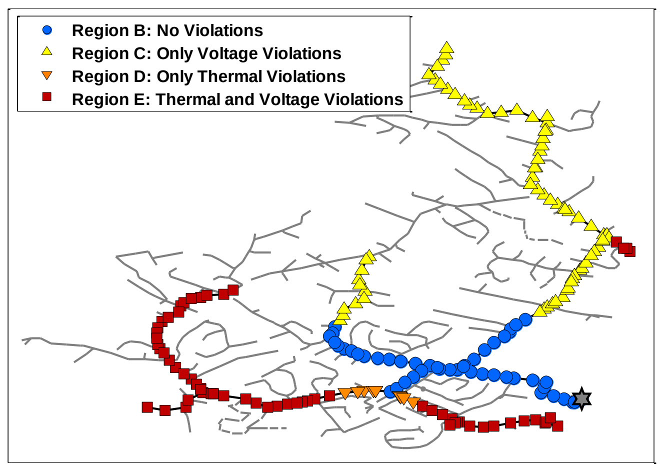


Fig. 7. Feeder interconnection zone map of 3-phase line sections for a 6 MW PV plant on Ckt5.

B. *Simplified Predictive PV Locational Hosting Capacity*

Simple techniques can be used to model the likelihood of feeder impact due to high penetration PV based on the feeder type, feeder characteristics and topology, PV location, PV plant size and configuration, and deployment level. The analysis and screening criteria could include available parameters such as short circuit current, impedance to the nearest upstream voltage regulation device, and upstream/downstream loads. A simple formula has been created for approximating feeder voltage as a function of the voltage regulation set-point of the upstream voltage regulator, impedance to the voltage regulator, and PV size. Using only these three variables, the PCC voltage can be approximated for any PV size. For the thermal violations, the line loading can be calculated using the load downstream of the PV PCC and the conductor type. With approximations for the PV impact to voltage and line loading, a simplified predictive algorithm can be applied to each bus to determine locational PV hosting capacity. The results of the maximum allowed PV size at each bus are shown in Fig. 8, and the approximate hosting capacity is shown in Fig. 9. As a very simple proof of concept, it is easy to see how closely the maximum PV size can be approximated from a few circuit parameters. With changing topology and variations in feeders, the method will need to account for other considerations, but this demonstrates that interconnections in Region B can be identified using simple parameters that could be used in the interconnection screening process.

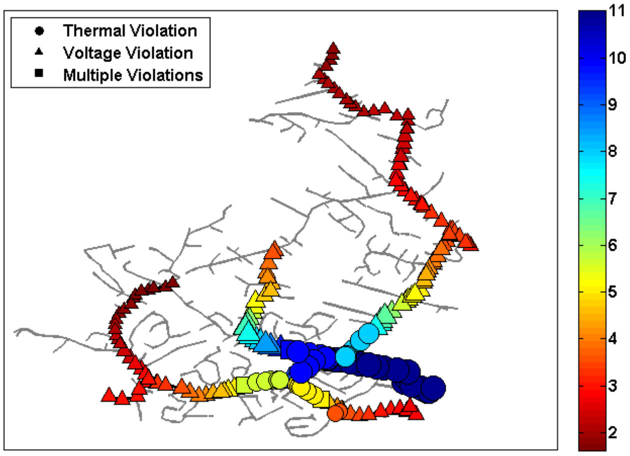


Fig. 8. Full analysis of locational hosting capacity for 3-phase line sections on Ckt5.

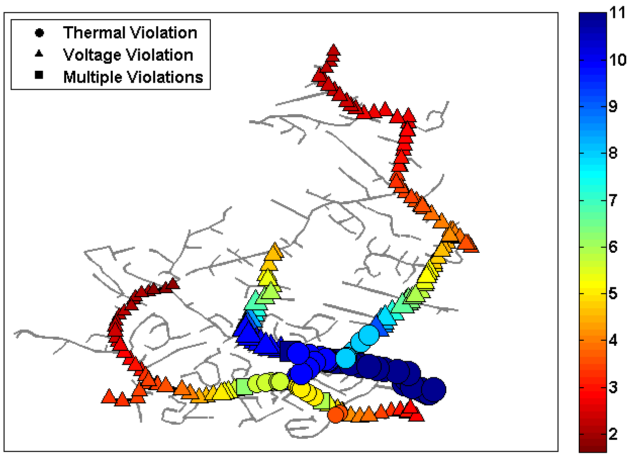


Fig. 9. Simplified predictive hosting capacity for 3-phase line sections on Ckt5.

VI. CONCLUSIONS

The simulation results presented show how a PV hosting capacity analysis can be used to obtain a feeder impact signature. This feeder signature separates a feeder into different impact regions that present varying amounts of PV interconnection risk. The regions relate to specific zones of the feeder where PV: is easily interconnected, possibly requires some impact mitigation strategies, or definitely presents risks that may be cost-prohibitive. Incorporation of locational information improves the speed and accuracy of the interconnection screening process by providing a more technically-based determination of the PV limits of a feeder. It was also shown how simple feeder characteristics such as voltage regulation set-points, conductor type, and distance to the substation can reasonably predict the locational hosting capacity. This analysis will be expanded to a larger set of feeder topologies and PV interconnection types in future work.

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