21, rue d'Artois, F-75008 PARIS
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Locational Impact of Distributed Generation on Feeders

M. ZILLMAN, D. APOSTOLOPOULOU, E. A. PAASO, M. AVENDANO-MORA
Commonwealth Edison Company
USA

SUMMARY

In this paper, a stochastic simulation framework to quantify the effect of distributed generation (DG) on distribution feeders is proposed. The approach focuses on the locational impact of distributed generation on feeder voltage and thermal limits. To this end, the proposed framework deploys distributed generation in various locations and sizes to determine the amount of distributed generation a feeder may accommodate without augmentation, i.e., its hosting capacity. More specifically, a sensitivity analysis is performed to demonstrate that the location of distributed generation installation greatly affects the voltage levels at the feeder nodes and thus its hosting capacity. It was also found that the electrical distance of the node where distributed generation is installed from the source plays an important role in defining the feeder's hosting capacity. The proposed ideas are demonstrated in a real utility feeder and several applications of the proposed framework are discussed.

KEYWORDS

Distributed generation, Hosting capacity, Sensitivity analysis, Stochastic simulation framework

Aleksi.Paaso@ComEd.com

1. INTRODUCTION

Distribution feeders are experiencing significant growth in distributed generation (DG) installations. This growth is largely due to: reducing costs of DG technologies, attractive incentive schemes, legislative mandates, and renewable generation targets. Although DG provides diversity in generation and can enable the development of more robust distribution systems, increased penetration also poses a number of technical challenges [1-3]. These technical issues include, but are not limited to: voltage regulation and imbalance, capacity constraints, reverse power flow, reduction of protection reach and loss of coordination, and (in the case of inverter-based systems) the introduction of harmonics.

Understanding the impact of DG technologies on the distribution system can aid in sustainable uptake of these technologies. In small quantities, it may be feasible to undertake detailed analysis of each DG interconnection request. However, as interest in DG increases, completing detailed studies may not be viable. To expedite the interconnection assessment process within the US, the Federal Energy Regulatory Commission (FERC) has developed interconnection requirements for Small Generation Facilities, which is a heuristic set of assessment guidelines for DG units that are less than 2 MW in size [4]. Although these assessment standards provide a well-constructed set of criteria for assessment, they do not take into account specific feeder characteristics, often resulting in conservative limits [5].

To address this issue, a number of techniques have been developed to provide more realistic estimates of the amount of DG a feeder can accommodate. This limit is commonly referred to within literature as the DG hosting capacity of a feeder or hosting capacity (HC) and is quantified in kW or MW. HC is defined as the maximum amount of new power production that can be connected without endangering the reliability or power quality for other customers [6]. One method commonly used to calculate HC employs a stochastic approach, modelling a large number of DG scenarios (i.e., varying locations and penetration levels of DG) [7]. This method is highly detailed and provides an accurate estimate of HC; however, it is computationally burdensome and time consuming. To reduce the computational complexity a modified method was proposed in [8], which is based on the results of [7] and provides a more readily scalable approach at the expense of a more conservative estimate of feeder HC.

The results of these techniques have demonstrated that the location and sizing of DG significantly impact the HC of a feeder. To better understand and quantify this impact, this paper extends the stochastic approach outlined in [7] to build a systematic algorithm for calculating the locational sensitivity of a feeder with respect to the size of DG.

2. TERMINOLOGY AND DEFINITIONS

There are a number of terms used when discussing the HC: The minimum HC (HC_{min}) corresponds to the penetration of DG where feeder constraints are first violated and is a worst-case scenario. Conversely, the maximum HC (HC_{max}) is the highest penetration of DG that can possibly be accommodated without violation of a feeder constraint. For the range of DG penetration between HC_{min} and HC_{max}, the ability of the feeder to accommodate DG becomes reliant on DG location. The distributed hosting capacity (HC_D) is the random variable that describes this relationship. It relates a given level of DG penetration on a feeder to the probability of a constraint violation occurring.The centralized hosting capacity (HC_C) is defined as the maximum amount of DG that could be installed at a single location on the feeder without resulting in a constraint violation.

To understand the locational impact of DG on a feeder, this paper introduces a new metric, the locational marginal hosting capacity (MHC_L). The MHC_L quantifies the change in the distributed hosting capacity of a feeder, i.e. $\Delta F_{HCD-1}(p|P_{DG}(n))$, at a defined probability (p) with the addition of DG generation (P_{DG}) to a fixed node (n). In this way, each node studied in a feeder would have a MHC_L that can be used to rank the impact of installing DG on a specific node relative to other nodes, and is defined as:

$$MHC_L\big(n_1 P_{DG}(n)\big) = \frac{\Delta F_{HC_D}^{-1}(p|P_{DG}(n))}{P_{DG(n)}}$$

From the analysis conducted it was determined that the value of MHC_L depends on the electrical distance of the node from the source. The definition of electrical distance for transmission systems is given in [9]. In a similar way, the electrical distance of a node from the source can be defined for a distribution system based on the Thevenin equivalent impedance

$$a(n) = \left|Z_{\phi}\right|^{2} = R_{\phi}^{2} + X_{\phi}^{2}$$

Where ϕ represents the electrical phase Z_{ϕ}, is the Thevenin equivalent impedance, and R_{ϕ} and X_{ϕ} are the resistance and susceptance, respectively. Per phase values are utilized in this instance as small DG systems (the focus of the algorithm) are likely to consist of single-phase systems. This is in comparison to larger installations that would be connected in a three-phase configuration.

3. PROPOSED SIMULATION FRAMEWORK

The following section outlines the core components of the simulation framework that was utilized to calculate the HC_D, HC_C and MHC_L.

A. Distributed Hosting Capacity Simulation

The calculation of HC_D forms the basis of the simulation framework and is implemented using a stochastic analysis technique similar to that outlined in [7]. The process for calculating HC_D, which is documented in Figure 2, has two core processes, a Feeder Study and related Feeder Scenarios. The Feeder Study component implements a Monte Carlo simulation [10] by running *M* different Feeder Scenarios. Each Feeder Scenario, which starts with the minimum feeder loading, incrementally adds DG to random locations on the feeder (with step size K in kW). With each iteration, the feeder is simulated and checked for constraint violations. The DG penetration at which a constraint violation occurs for each scenario is captured. In this way, the Monte Carlo simulation generates a set of DG penetration levels for a given locational distribution of DG. Using this sampled data and applying the kernel density estimation (KDE) method [11], it is possible to obtain a smoothed version of the empirical pdf ($f_{HCD}(x)$) and cdf ($F_{HCD}(x)$), as shown in Figure 1.

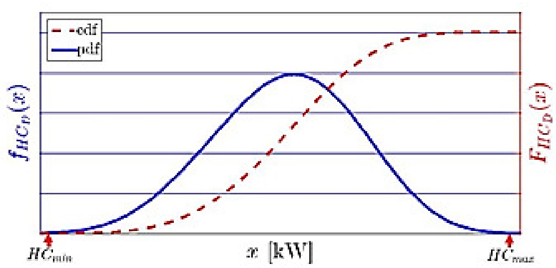

Figure 1: Representative feeder hosting capacity probability denstiny function (pdf) and cumulative destiny function (cdf)

B. Centralized Hosting Capacity Simulation

The calculation of HC is one conceivable permutation of HC_D; however, given the statistically improbable nature of this scenario a targeted modelling approach was implemented specifically to identify HC_C. This method utilizes a similar process to that outlined in Figure 2, but rather than randomly allocating DG across the feeder, the process iterates over each customer adding DG until a feeder constraint violation is observed.

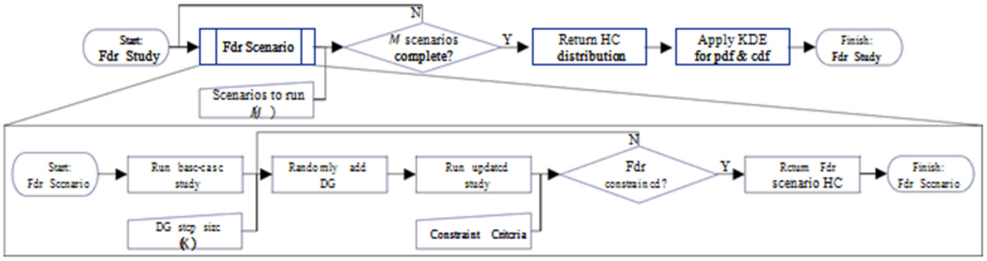

Figure 2 : Distibuted generation hosting capacity HC_D feeder (Fdr) simulation process

C. Locational Sensitivity Simulation

By establishing a hybrid of these methodologies, it is possible to estimate the MHC_L of defined location. This process fixes a defined amount of DG to a single customer node ($P_{DG}(n)$) and recalculates the distributions of (x) and (x). It follows that after a number of such iterations, the function that depends on the selected probability (p) and ($P_{DG}(n)$), can be approximated. This process can then be scaled to a number of different nodes on the feeder to understand the locational sensitivity of different feeder nodes.

4. REAL FEEDER TEST CASE

This section illustrates the proposed concepts and stochastic framework with a real utility feeder. The study feeder is a 12kV feeder that contains 1026 nodes, 1044 lines, and 208 spot loads with a mixture of single and multi-phase configurations, as well as unbalanced loading conditions. The one line diagram of the feeder is depicted in Figure 3.

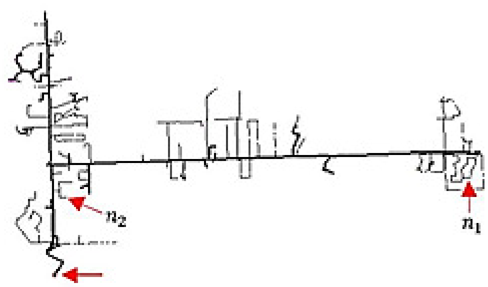

Figure 3: One-line diagram of the real utility feeder

A. Distributed and Centralized Hosting Capacity

In order to determine the pdf of the distributed hosting capacity HC_D, the stochastic simulation framework is run M = 1,200 times with K = 25 kW. The resultant histogram of HC_D is depicted in Figure 4, and by applying the KDE method to this data a smoothed pdf is calculated. From Figure 4 it is possible to determine the probability of a certain DG penetration level causing a constraint within the feeder, as seen in Table 1. The values of HC_{min} and HC_{max} from this simulation are 1,400 kW and 3,290 kW, respectively. Next, the centralized hosting capacity of the feeder (HC_C) is calculated and found to be 350 kW. The single location that constrains the centralized hosting capacity was found to be a large electrical distance from the substation.

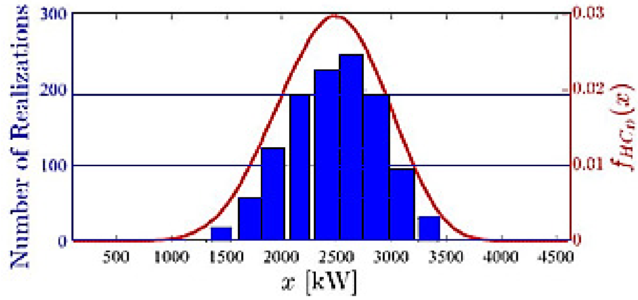

Figure 4: Probability density function (pdf) of the distributed hosting capacity random variable (HC_D)

Table 1: Percentage of observations where no constraints occurred based on DG penetration level			
Observations with no constraints	95%	50%	5%
Penetration level	1664 kW	2479 kW	3145 kW

B. Locational Sensitivity of Distributed Hosting Capacity

This subsection presents the analytical results of the MHC_L for two representative nodes within the study feeder. The two nodes $N = \{n_1, n_2\}$ differ in terms of electrical distance from the substation. More specifically, the electrical distance is $a(n_1) = 28.74$, and $a(n_2) = 2.25$ in pu for each of the two nodes. In order to determine the locational sensitivity, 200 scenarios (i.e. $M = 200$) for each level of the DG penetration at the node (i.e. $P_{DG}(n)$) were applied.

1) Locational Sensitivity for Node n_1

Figure 5 depicts the conditional probabilities of the distributed hosting capacity for various penetrations of DG at node n_1. It is notable that as the DG penetration at node n_1 increases the pdf shifts to the left and is more skewed. Table 2 shows the distributed hosting capacity with 50% probability for various penetrations of DG at node n_1. The results obtained were expected since node $n_1$is located far from the source of the feeder, as seen by its electrical distance n_1, and the overvoltage concerns are exacerbated. As the amount of DG at node n_1 is increased, the number of permutations of DG installation location within the remainder of the feeder that will result in a constraint is increased; thus HC_D of the feeder is reduced, as seen in Table 2. The highest penetration level at this node that does not violate any voltage or thermal limits is 400 kW. This number is larger than the centralized hosting capacity, which is 350 kW; thus, there is another node that constrains the feeder's centralized hosting capacity. Using the data points given in Table 2, the locational marginal hosting capacity with probability 50%, i.e. $\Delta F_{HCD}^{-1}(0.5|P_{DG}(n_1))$, is calculated as depicted in Figure 7. It can be seen that there is a linear relationship between the change in the HC_D for a given probability and the size of DG at node n_1. Using linear regression, it was found that $MHC_L(0.5, P_{DG}(n_1)) = 4.88$. Moreover, this number stays constant for all levels of DG penetration. The sensitivity with respect to the probability value is demonstrated in Figure 7. It is evident from this figure that for values of p between 0.35 and 0.75 the value of MHC_L is consistent and the maximum relative error of the mean value is 8.6%.

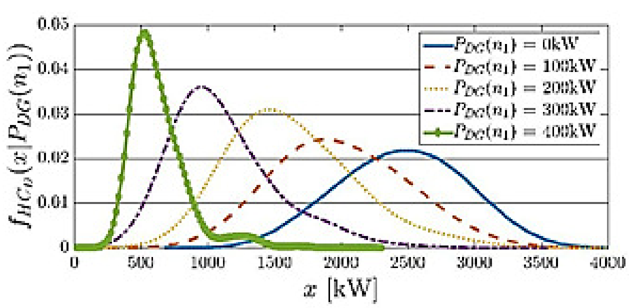

Figure 5: Conditional pdfs of distributed hosting capacity (HC_D) for n_1 based on P_{DG}

Table 2: Conditional Hosting Capacity based on DG penetration level at n_1								
$P_{DG}(n_1)$ [kW]	50	100	150	200	250	300	350	400
$F^{-1}_{HCD}(0.5\|P_{DG}(n_1))$ [kW]	2385	1876	1825	1461	1265	967	750	528

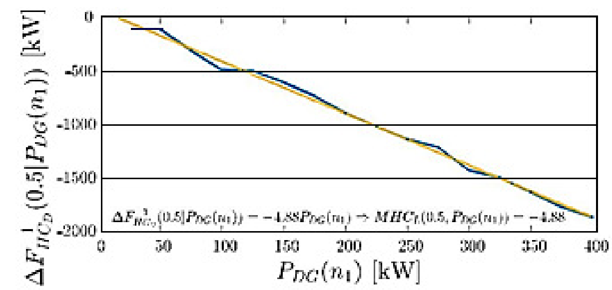

Figure 6: Locational marginal hosting capacity (MHC_L) with probability (p) 0.5 at n_1

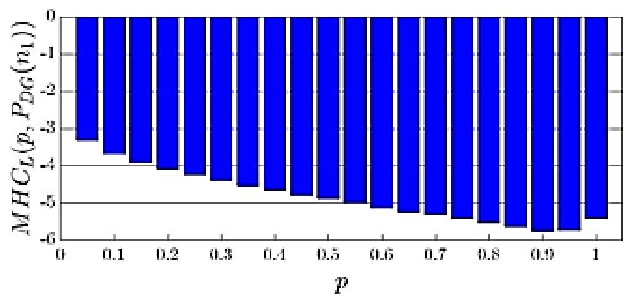

Figure 7: Sensitivity of MHC_L with respect to probability p at n_1

2) Locational Sensitivity of Node n_2

The smaller electrical distance of n_2 (compared to that of n_1) reduced the sensitivity of HC_D to DG at this node; therefore, larger steps in DG penetration were utilized in the simulator process, which covered DG penetration from 200 kW to 1,600 kW in 200 kW steps. A selection of representative conditional pdfs are depicted in Figure 8. In this case, it can be seen that for amounts up to 1200 kW the pdf is shifted to the right, i.e. the HC_D of the feeder is improving. This occurs because installing DG close to the source of the feeder is similar to increasing the generation from the source. Thus, no voltage or thermal constraints are likely to be violated. Since a portion of the DG is fixed at a favorable location, the HC_D of the feeder increases. However, when HC_{max} is reached, which is equal to 3,290 kW, then the pdf of HC_D shifts again to the left, as seen for $P_{DG}(n_2)$ = 1,600 kW.

In this case, the MHC_L has a more complicated relationship than in the case of node n_1. The reason is that at small DG penetrations the HC_D of the feeder increases until the HC_{max} is reached and a reverse effect is observed. In Figure 9, the relationship between the change in the 50% probability HC_D and the size of DG is shown. The two curves are approximated with two linear relationships using linear regression. At 1,190 kW the turning point is observed. It is believed that this occurs because the pdf of HC_D for $P_{DG}(n_2)$ = 1,190kW, is skewed to the HC_{max}, which is the upper limit of the feeder HC. Therefore, for penetration levels at node n_2 above 1,190 kW, the pdf cannot skew further, i.e. $\Delta(0.5| P_{DG}(n_2))$ cannot be positive.

From the locational sensitivity analysis at nodes n_1 and n_2, it may be concluded that the electrical distance of a feeder node has a large impact on the sensitivity of the feeder's HC_D. It is also noted that an intuitive simple subtraction of the size of DG deployed from the initial hosting capacity does not result in the new hosting capacity. As this analysis has shown, 1 kW of DG installed at node n_1 decreased the hosting capacity by approximately 5kW. Thus, the calculation of the locational sensitivity of a feeder's hosting capacity with respect to a DG installation at node is complicated and useful in several applications.

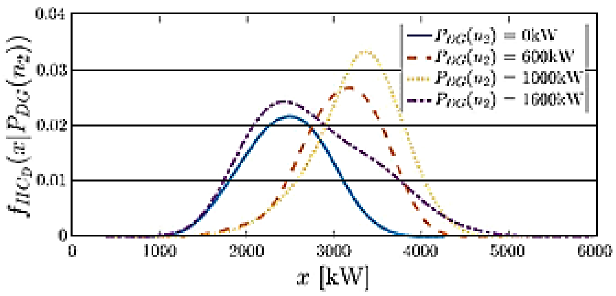

Figure 8: Conditional pdfs of distributed hosting capacity (HC_D) for n_2 based on P_{DG}

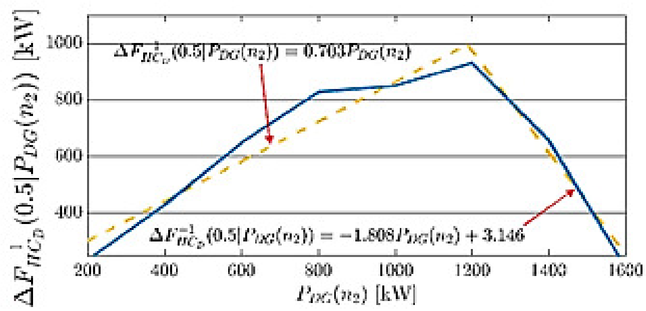

Figure 9: Locational marginal hosting capacity (MHC_L) with probability (p) 0.5 at node n_2

5. APPLICATION OF ANALYSIS

Once quantified, the MHC_L could find use in a number of applications in sustainably integrating DG within distribution systems. In particular, the MHC_L will assist in:

- Distribution system planning and development of processes to identify locations for optimal placement of DG.
- Developing targeted incentive programs that encourage installation of DG in locations that minimize the impact on feeder performance.
- Monitoring and measuring the impact of DG on the distribution system over time.

6. CONCLUSION

This paper presented a simulation framework for analyzing the locational impact of DG on distribution feeders. This framework was applied to a real feeder, showing representative results for two nodes and highlighting the impact of installing DG at these locations on the feeder HC. In particular, the results demonstrated the strong locational sensitivity of the study feeder to DG, with installation of DG on one node reducing the feeder HC by 5kW for every 1kW of DG installed. This sensitivity was found to be strongly linked to the electrical distance of the node from the source.

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