21, rue d'Artois, F-75008 PARIS
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A Fast Hosting Capacity Calculation Method for Large Distribution Grids

M. ALTURKI, A. KHODAEI
University of Denver
USA

E.A. PAASO
ComEd
USA

SUMMARY

The growing deployment of distributed generation (DG) units offers considerable advantages to the energy sector including clean renewable energy (e.g. solar PV and wind) and reduced energy distribution costs. However, the increased integration of DGs into existing distribution networks is impacting their behavior in terms of voltage profile, reliability, and power quality. To prevent these adverse impacts, a determination of the network's hosting capacity is required. The term "hosting capacity" is defined as the maximum DG capacity that a distribution network can accommodate without violating recommended operating constraints. By optimizing the hosting capacity, distribution system operators are able to incorporate more DG without requiring any system upgrades and/or new investments. The traditional methods of determining the hosting capacity are commonly computationally intensive, rendering them impractical in many real-world conditions. This paper presents a sensitivity-based method that can significantly reduce computation requirements. Numerical simulations are performed on modified 123-bus distribution test system to demonstrate the effectiveness of the proposed method.

KEYWORDS

Distributed generation, Hosting capacity, Sensitivity analysis.

Mansoor.Alturki@du.edu

1. INTRODUCTION

In the past few decades, there has been a slow but consistent shift in the energy industry from centralized large-scale energy production to distributed localized generation. The distributed generation (DG) technologies provide a set of economic and environmental benefits by reducing power generation costs, supporting deployment of renewable energy sources, and increasing the systems' overall energy efficiency. Integrating DGs into existing networks, however, causes changes in voltages and currents throughout the distribution network and can potentially result in critical issues in system operation such as fluctuations in the voltage profile and reduced system stability to name a few [1]. By adopting a methodology which addresses these concerns, distribution system operators can safely maximize the amount of injected DG power.

In practice, methodologies for evaluating and optimizing DG hosting capacity have been technically challenging. Solving such problems often requires either extensive computational resources or sophisticated analytical and computational techniques. Various optimization methods have been proposed in the literature to optimize DG hosting capacity in distribution networks. A variety of objectives and operational constraints are considered in the existing methods. Some studies choose, for instance, to maximize the total DG injection (hosting capacity) while enforcing operational constraints such as voltage, thermal, and harmonic distortion limits [2]–[4]. Other methods use similar operational constraints while focusing on other objectives such as the reduction of system losses [5], improvement of voltage profiles [6], reduction of operating costs [7], and reduction of environmental impacts [8]. These studies commonly rely on an AC power flow analysis to simulate the distribution system's operation. Ideally, predicting the behavior of distribution systems with high fidelity should increase the reliability of the analysis. However, because the AC power flow methods are computationally intensive, an extensive number of scenarios cannot be analyzed within practical time limits. With fewer scenarios to analyze, the optimization search space will decrease and the optimal solution's accuracy will improve. The outcome illustrates that while AC power flow analysis provides mathematically precise results, their difficult execution may lead to a less reliable solution.

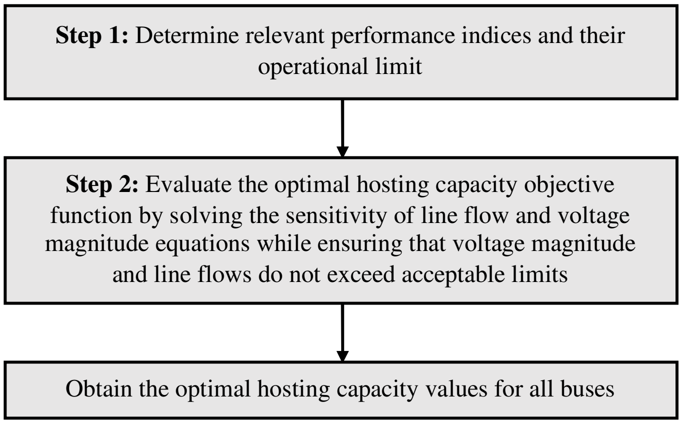
Traditional optimization of DGs in distribution networks is computationally intensive for two reasons: nonlinearity and large search spaces. Optimizing DG hosting capacity in distribution networks involves nonlinear AC power flow equations. Consequently, optimization traditionally relies on nonlinear solvers with undesirably long runtimes. Additionally, each bus that can accommodate DG will contribute an independent variable to the search space. Sampling such a search space requires performing AC power flow analysis for each potential DG profile. Since the number of DG profiles grows rapidly with the number of active buses, optimization of larger systems becomes impractical. For example, to analyze the impact of DG hosting capacity in the IEEE 123-bus system in a single location with DG power increments of 1 kW, it would take more than 9100 test runs to consider all possible scenarios. If the DG hosting capacity is considered to be in two different locations at the same time, this number would increase to more than 20 million test runs. This paper addresses these issues by using a sensitivity-based method focused on voltage and line flows to reduce the complexity of calculations. The proposed method uses an optimization approach that reduces the number of variables in the search space, avoids extensive iterations, and significantly reduces the runtime while providing results comparable with traditional methods. The smaller computation time allows distribution system operators to scale up the optimization to larger systems without losing the robustness. For additional robustness, load uncertainties are considered to obtain a conservative grid hosting capacity solution.

The rest of the paper is organized as follows. Section 2 presents the mathematical formulation of the proposed sensitivity-based optimization method. Numerical simulations on the IEEE 123-bus distribution test system are presented in Section 3 to show the effectiveness of the proposed method. Conclusions are provided in Section 4.

2. SENSITIVITY-BASED HOSTING CAPACITY OPTIMIZATION METHOD

The objective of the proposed method is to maximize the amount of DG hosting capacity in an active distribution network without negatively affecting the operational performance of the network. A comprehensive optimization should explore the effects of injecting varying amounts of DG generation into various locations simultaneously. However, each possible location for DG installation introduces another variable to be optimized, causing an exponential increase in the computation required as more buses are considered. Sensitivity analysis can overcome this problem by simplifying the optimization problem. This is conducted by considering the effect of variations of DG power in each location on the system's steady-state bus voltages and line flows.

Sensitivity analysis relies on the linearization of the nonlinear power flow equations around the initial operating conditions. This permits a reduction of the number of solutions required for DG injection. Figure 1 illustrates the flowchart of the proposed method. In step one, operational performance indices are defined that measure whether the performance of the system is within the acceptable limits. For each performance index, operational upper and lower bounds are defined within which the system is operating properly (e.g. thermal limits and voltage limits). The sensitivity-based method used here may be generalized to any operational performance index defined based on the operational behavior of the distribution system (i.e., emphasizing different operational concerns). In step two, the sensitivity analysis of the line flow and voltage magnitude is performed while enforcing limits defined in step 1. The results obtained from step two will be the optimal DG hosting capacity.



Step 1: Determine relevant performance indices and their operational limit

Step 2: Evaluate the optimal hosting capacity objective function by solving the sensitivity of line flow and voltage magnitude equations while ensuring that voltage magnitude and line flows do not exceed acceptable limits

Obtain the optimal hosting capacity values for all buses

Figure 1: The proposed hosting capacity method.

Linear sensitivity factors: To determine the impact of DG integration in active distribution networks, AC power flow analysis is commonly utilized, however, it is nonlinear and time consuming. To simplify the complexity in nonlinear power flow analysis, a linear power flow model is adopted in this paper. To develop the linear model, first the nodal voltage magnitudes and angles are defined (with no approximation) based on their respective value change from the point of interconnection, i.e., the change in voltage magnitudes and angles in a selected bus m are defined as $V_m=1+\Delta V_m$ and $\theta_m=0+\Delta\theta_m$. In addition, two assumptions are made: First, the difference in voltage phase angle of adjacent buses is considered to be small, so a trigonometric approximation can be made to linearize these terms by assuming that $\sin(\Delta\theta_m-\Delta\theta_n)\approx \Delta\theta_m-\Delta\theta_n$ and $\cos(\Delta\theta_m-\Delta\theta_n)\approx 1$. The second assumption is that the multiplication of the change in voltage magnitudes and angles, i.e., ΔV times $\Delta\theta$ terms, are small and can be ignored. These assumptions are valid in normal operating conditions. Based on these assumptions, the active and reactive power injections at bus m can be defined as follows:

$$P_m=\sum_n\left(g_{mn}(1+\Delta V_m)(\Delta V_m-\Delta V_n)-b_{mn}(\Delta\theta_m-\Delta\theta_n)\right) \qquad \forall m,n\in \mathrm{B} \tag{1}$$

$$Q_m=\sum_n\left(-b_{mn}(1+\Delta V_m)(\Delta V_m-\Delta V_n)-g_{mn}(\Delta\theta_m-\Delta\theta_n)\right) \qquad \forall m,n\in \mathrm{B} \tag{2}$$

where, g and b are the line conductance and susceptance, respectively, and B is the set of all buses. By assuming ΔV_m (in the term $1+\Delta V_m$) is zero, system losses will be ignored and thus these equations would convert to linear equations. Based on (1) and (2), the active and reactive injected power can be defined in matrix form as follows:

$$\begin{bmatrix}\mathbf{P}\\ \mathbf{Q}\end{bmatrix}=\begin{bmatrix}\mathbf{G} & \mathbf{-B}\\ \mathbf{-B} & \mathbf{-G}\end{bmatrix}\begin{bmatrix}\mathbf{\Delta V}\\ \mathbf{\Delta\theta}\end{bmatrix} \tag{3}$$

Here, **P** and **Q** are respectively the injected active and reactive power, **G** and **B** are respectively the conductance and susceptance matrices, and **ΔV** and **Δθ** are, respectively, the change in voltage magnitude and angle with respect to the point of interconnection. The voltage sensitivity factors (VSF) with respect to the active and reactive injected power can be easily calculated from (3) as:

$$\mathbf{VSF}^{P}=(\mathbf{B}^{-1}\mathbf{G}+\mathbf{G}^{-1}\mathbf{B})^{-1}(\mathbf{B}^{-1}) \tag{4}$$

$$\mathbf{VSF}^{Q}=(\mathbf{B}^{-1}\mathbf{G}+\mathbf{G}^{-1}\mathbf{B})^{-1}(\mathbf{-G}^{-1}) \tag{5}$$

Based on the injected power and the line flow equations, the active and reactive line sensitivity factors (LSF) can also be calculated as:

$$\mathbf{LSF}^{P}=\mathbf{D(g)A}(\mathbf{B}^{-1}\mathbf{G}+\mathbf{G}^{-1}\mathbf{B})^{-1}(\mathbf{B}^{-1})+\mathbf{D(b)A}(\mathbf{B}^{-1}\mathbf{G}+\mathbf{G}^{-1}\mathbf{B})^{-1}(\mathbf{-G}^{-1}) \tag{6}$$

$$\mathbf{LSF}^{Q}=\mathbf{-D(g)A}(\mathbf{B}^{-1}\mathbf{G}+\mathbf{G}^{-1}\mathbf{B})^{-1}(\mathbf{G}^{-1})+\mathbf{D(b)A}(\mathbf{B}^{-1}\mathbf{G}+\mathbf{G}^{-1}\mathbf{B})^{-1}(\mathbf{B}^{-1}) \tag{7}$$

Here, **D(g)** and **D(b)** are diagonal matrices of the lines conductance and susceptance, respectively. **A** represents the bus-line incidence matrix.

Line limits: For the line connecting buses m and n, the active power flow PL_{mn} is defined based on the line sensitivity factors (LSF) as follows:

$$PL_{mn} = \sum_{n \in L_m} (LSF^P_{mn,i} P_i + LSF^Q_{mn,i} Q_i) \qquad \forall mn \in \mathrm{L}, \forall i \in \mathrm{B} \tag{8}$$

In (8), $LSF^P_{mn,i}$ and $LSF^Q_{mn,i}$ are the active and reactive line sensitivity factors of the line connecting buses m and n subject to the power injection at bus i. P_i and Q_i are the net injected active and reactive power at bus i, defined respectively as $P_i = P_i^{DG} - P_i^D$ and $Q_i = Q_i^{DG} - Q_i^D$. P_i^{DG} and Q_i^{DG} are the active and reactive power generated by DG at bus i, and P_i^D and Q_i^D are the active and reactive load at bus i. Assuming a constant power factor for injected DG, a constant parameter α can be defined as the ratio of the reactive power to the active power. With this assumption, the net injected reactive power can be defined as $Q_i = \alpha P_i^{DG} - Q_i^D$.

To simulate the impact of load variations, the worst-case scenario should be taken into account. This step is taken to guarantee that the system performs within the acceptable limits regardless of variations in load. The line limit is represented using LSFs as follows:

$$PL^{adj,\min}_{mn} \le \sum_{n \in L_m} (LSF^P_{mn,i} P_i^{DG} + LSF^Q_{mn,i} \alpha P_i^{DG}) \le PL^{adj,\max}_{mn} \qquad \forall mn \in \mathrm{L}, \forall m,i \in \mathrm{B} \tag{9}$$

In (9), the bounds represent the adjusted active power flow limits of line mn. The lower and upper adjusted limits are calculated as:

$$PL^{adj,\min}_{mn} = -PL^{\max}_{mn} + \min\left(\sum_{n \in L_m} (LSF^P_{mn,i} P_i^D + LSF^Q_{mn,i} Q_i^D) \right) \qquad \forall mn \in \mathrm{L}, \forall i \in \mathrm{B} \tag{10}$$

$$PL^{adj,\max}_{mn} = PL^{\max}_{mn} + \min\left(\sum_{n \in L_m} (LSF^P_{mn,i} P_i^D + LSF^Q_{mn,i} Q_i^D) \right) \qquad \forall mn \in \mathrm{L}, \forall i \in \mathrm{B} \tag{11}$$

Here, PL_{mn}^{max} is the maximum line capacity limit, and 'min' ensures that the most restricting limit, i.e., the worst-case is applied.

Voltage limits: The voltage constraint, in terms of the VSF with respect to the active and reactive injected power, can be expressed as:

$$\Delta V^{adj,\min}_{m} \le \sum_{m} (VSF^P_{m,i} P_i^{DG} + VSF^Q_{m,i} \alpha P_i^{DG}) \le \Delta V^{adj,\max}_{m} \qquad \forall m,i \in \mathrm{B} \tag{12}$$

The bounds represent the adjusted voltage magnitude limits are defined as:

$$\Delta V^{adj,\min}_{m} = \Delta V^{\min}_{m} + \min\left(\sum_{m} (VSF^P_{m,i} P_i^D + VSF^Q_{m,i} Q_i^D) \right) \qquad \forall m,i \in \mathrm{B} \tag{13}$$

$$\Delta V^{adj,\max}_{m} = \Delta V^{\max}_{m} + \min\left(\sum_{m} (VSF^P_{m,i} P_i^D + VSF^Q_{m,i} Q_i^D) \right) \qquad \forall m,i \in \mathrm{B} \tag{14}$$

V_m^{min} and V_m^{max} are respectively the lower and upper voltage limits in bus m.

Hosting capacity calculation: Based on the calculated sensitivity factors, the hosting capacity calculation model can be developed as follows:

$$\max \quad \sum_i P_i^{DG} \tag{15}$$

subject to (9) and (12).

The objective function of the proposed model is to maximize the total network DG hosting capacity (15) that is subject to the line capacity (9) and voltage magnitude (12) limits. The uncertainties in load are integrated into the model through adjusted line and voltage limits. This model has only one variable, i.e., P^{DG}, so it can be solved in a very short amount of time even for very large-scale problems.

3. NUMERICAL SIMULATIONS

The modified IEEE 123-bus distribution test system shown in Figure 2 is used to show the performance of the proposed method. This distribution test system contains 123 buses and 122 lines and is structured radially [9]. Two different scenarios are performed on the distribution test system, each using a different load condition. The first scenario uses base-load values to represent typical load conditions, while the second scenario uses uncertain-load values to represent worst-case load conditions. Values for base and uncertain loads are derived from historical data collected over a year-long period. Uncertain load values are constrained by lower and upper bounds defined as the lowest and highest load values over the aforementioned period. To determine the worst-case optimal hosting capacity, loads that minimize the optimal hosting capacity are selected from the uncertain-load profile. The optimal hosting capacity for uncertain loads can thus be interpreted as the optimal hosting capacity that guarantees acceptable hosting capacity regardless of load variations. The total active and reactive load on the system for the base-load condition is 4.925 MW and 2.705 MVAR, while the worst-case load profile totals to 2.708 MW and 1.487 MVAR. Exchange power flowing from the distribution network to the upstream grid is capped at 6.44 MW. This is the active power limit of the substation, i.e., the maximum power that can flow back from the distribution network to the upstream grid through the substation.

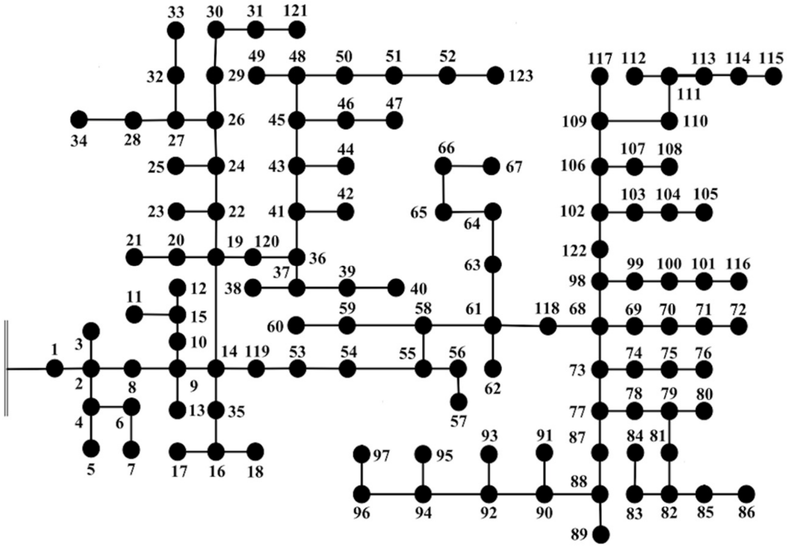


Figure 2: The IEEE 123-bus distribution system.

Case 1: Comparison with the traditional iterative method: This case compares the proposed method with traditional iterative method in terms of computation time and solution accuracy. The sensitivity-based and the traditional iterative hosting capacity methods are applied to the same distribution test system using the base-load scenario to determine the optimal DG hosting capacity. In addition, both scenarios are initialized with the same operational constraints (i.e. thermal and voltage limits) to facilitate a direct comparison. In the traditional iterative method, a DG with a 1 kW step size was selected to determine the individual hosting capacity. The optimal individual hosting capacities for buses 4, 63, and 98 (that are randomly selected to illustrate the accuracy of the proposed method) are 6.564 MW, 2.862 MW and 2.990 MW, respectively. Using the proposed sensitivity-based method, the optimal hosting capacity for the same selected buses are 6.218 MW, 2.686 MW, and 2.831 MW, respectively. The comparison of these arbitrarily-selected solutions demonstrates the acceptable accuracy of the proposed method. Checking the results for all buses, the highest deviation in results is obtained as 5.42%. The time required to determine the individual DG hosting capacity using the proposed method is less than 2 s, while the traditional method requires an average of 18 minutes. This applies a single-bus hosting capacity calculation; more time would be required for combinations of 2 and higher buses. These results demonstrate a clear improvement in the required runtime with only a slight decrease in solution accuracy.

Case 2: Impact of load variations: In this case, the proposed method is used to calculate the optimal hosting capacity for both base and uncertain load scenarios. The network optimization permits the installation of additional DGs in all buses simultaneously. In other words, DGs are allowed to be installed in all buses at the same time. Table 1 compares the obtained results from both scenarios. For the base-load optimization, the total hosting capacity is found to be 11.368 MW with 1.641 MW, 3.632 MW, 3.984 MW and 2.111 MW of DG power placed in buses 2, 3, 5, and 121. For the uncertain-load optimization, the total hosting capacity is found to be 9.151 MW with 1.156 MW, 1.215 MW, 3.966 MW, 0.721 MW, and 2.093 MW of DG power placed in buses 2, 5, 7, 117 and 121. In both scenarios the optimal hosting capacity was limited by the thermal limits, especially of the line connecting the distribution system to the upstream grid. Comparing the two scenarios, the load uncertainty reduces the optimal hosting capacity by 19.5% (from 11.368 MW to 9.151 MW). The exported DG power from the distribution system to the upstream grid in both scenarios is the same. In both scenarios, the overall runtime of the entire problem is less than 2 s.

Table 1: Optimal hosting capacity results for base-load and uncertain-load.

Bus Number	**Base-load hosting capacity (MW)**	**Uncertain-load hosting capacity (MW)**
2	1.641	1.156
3	3.632	0.0
5	3.984	1.215
7	0.0	3.966
117	0.0	0.721
121	2.111	2.093
Total DG	**11.368**	**9.151**

Case 3: In this case, the proposed method is compared with a linear hosting capacity model proposed in [2] that considers system losses. This comparison is needed to show if ignoring system losses in the sensitivity-based method impacts the results. In both methods, DGs are

allowed to be installed in all buses simultaneously using base-load profile. The optimal network hosting capacity in the proposed method is 11.368 MW. However, the optimal hosting capacity using the method in [2] is calculated at 11.788 MW. The difference between these two solutions is 3.56 %, which indicates the acceptable accuracy that can be provided using the sensitivity-based method.

4. CONCLUSION

A sensitivity-based hosting capacity calculation method was proposed in this paper to determine the optimal DG profile in an active distribution network. The problem was developed based on the sensitivity analysis of line power flow and voltage magnitudes with respect to nodal active and reactive injections. The advantage of using the sensitivity analysis was shown to be a reduction in the optimization complexity and accordingly the computation time. A demonstration of the sensitivity analysis method on the IEEE 123-bus distribution system showed its capability to provide the optimal DG hosting capacity within only 2 s. Load uncertainty was also considered to show the dependence of the hosting capacity on load variations as well as improving the robustness of DG integration in distribution networks. By using the worst-case load profile, a conservative hosting capacity would be obtained and would be valid for all variations in the load profile. Results showed that the proposed method could outperform traditional hosting capacity methods in terms of computation time while ensuring an acceptable accuracy. Finally, the simplicity of used equations in the proposed method permits scaling-up the analysis to larger systems without requiring long runtimes.

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