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Optimization-based distribution grid hosting capacity calculations

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HIGHLIGHTS

- An optimization-based hosting capacity method is developed.
- The distribution grid power flow is linearized.
- The spatial interdependency of DG deployments is considered.
- Load variations are accounted for based on robust optimization.

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ABSTRACT

The distribution grid hosting capacity is defined as the amount of new production or consumption that can be added to the grid without adversely impacting the reliability or voltage quality for other customers. In this paper, an optimization-based method for determining the hosting capacity in distribution grids is proposed. The proposed method is developed based on a set of linear power flow equations that enable linear programming formulation of the hosting capacity model. Linearization further helps with determining a near-optimal solution in a short amount of time. The proposed method is examined on a test radial distribution grid to show its effectiveness and acceptable performance. Performance is further measured against existing iterative hosting capacity calculation methods. Results demonstrate that the proposed method outperforms traditional methods in terms of computation time while offering comparable results.

1. Introduction

Distributed Generators (DGs) are small units of generation that are directly connected to the distribution grid and are in close proximity to consumers. There is a growing proliferation of DGs in distribution grids, conceivably due to the falling cost of the technology as well as the promising benefits for end-use electricity customers such as payment reduction and potential load-point reliability improvement [1–3]. Once installed, the associated customers will be regarded as “prosumers”, meaning that they are consumers that also have the ability to produce electricity. Among available DG technologies, solar photovoltaic (PV) and small-scale wind turbines perceived to be the most adopted DG technologies for prosumers. At the end of 2016, the grid-connected solar PV installation in the United States reached a total capacity of 36 GW [4], up from 25.6 GW in 2015 and 18.3 GW in 2014.

Although interesting options for end-use customers and viable solutions for system operators to shift the generation from large-scale power plants to small-scale distributed resources, the DG installation could cause several negative impacts on distribution grids. Most notably, growing DG installations may put the grid at risk of having inefficient and/or low-reliability supply, as some of operational quantities can potentially hit their limits and result in power quality or reliability concerns at the system and customer levels [5,6]. In this case, a variety of factors, such as the rise/drop in nodal voltages and power flow in distribution branches (i.e., lines and transformers), needs to be considered when adding DGs. To determine the maximum amount of DG that a distribution grid can accommodate the concept of hosting capacity is introduced. The hosting capacity is defined as the amount of new production or consumption which can be connected to the grid without adversely impacting the reliability or voltage quality for other customers [7]. The operational performance is measured using various factors, from voltage magnitudes to feeder power flows to power quality issues [8]. Protection can also be considered as a critical performance measure as the DG deployment will potentially result in a reverse power flow in distribution feeders. The hosting capacity calculation sheds light on the role and impacts of DGs within the distribution grids. It can further provide grid planners with the required insight on how to build and upgrade the grid in a cheaper, greener, and

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Nomenclature

Sets

C_m set of points of interconnection connected to bus *m*
L set of lines
L_m set of lines connected to bus *m*
B set of buses
Λ set of primal variables
U set of uncertain parameters

Indices

c index for points of interconnection
m, *n* index for buses
∧ index for calculated variables

Parameters

b_{mn} Susceptance of line *mn*
g_{mn} conductance of line *mn*
r_{mn} resistance of line *mn*
$P_m^{D,\max}$ upper limit of active load at bus *m*
$P_m^{D,\min}$ lower limit of active load at bus *m*
$P_c^{M,\max}$ maximum active power exchange with upstream grid at point of interconnection *c*
$PL_{mn}^{\max}$ maximum active power flow of line *mn*
$Q_m^{D,\max}$ upper limit of reactive load at bus *m*
$Q_m^{D,\min}$ lower limit of reactive load at bus *m*
$Q_c^{M,\max}$ maximum reactive power exchange with upstream grid at point of interconnection *c*
$QL_{mn}^{\max}$ maximum reactive power flow of line *mn*
x_{mn} reactance of line *mn*
$\Delta V_m^{\min}$ lower limit of voltage magnitude deviation in bus *m*
$\Delta V_m^{\max}$ upper limit of voltage magnitude deviation in bus *m*

Variables

P_m^D active load at bus *m*
P_m^G active power of distributed generation at bus *m*
P_c^M active power exchange with upstream grid at point of interconnection *c*
PL_{mn} active power flow at line *mn*
Q_m^D reactive load at bus *m*
Q_m^G reactive power of distributed generation at bus *m*
Q_c^M reactive power exchange with upstream grid at point of interconnection *c*
QL_{mn} reactive power flow at line *mn*
V_m voltage magnitude at bus *m*
θ_m voltage angle at bus *m*
ΔV_m voltage magnitude deviation in bus *m*
$\Delta\theta_m$ voltage angle deviation in bus *m*

more sustainable way. Hosting capacity calculations can also determine the maximum amount of DG that can be deployed to support reducing peak demand and postponing required grid upgrades.

The hosting capacity studies in the literature can be categorized into two main groups: (i) studies that propose hosting capacity calculation methods based on a variety of grid performance measures and system characteristics, and (ii) studies that focus on grid upgrades or operational practices to increase grid hosting capacity. Former studies further investigate the impact of DGs on selected operational performance measures as elaborated in [9,10]. These performance measures can be bus overvoltage, line overload, or power quality. The locational sensitivity analysis method of distribution feeders introduced in [11] estimates the grid hosting capacity by demonstrating the effect of DG distance on voltage deviations at feeder nodes. Similar studies are performed in [12] but with a focus on PV integration into distribution grids. Authors conclude that analyzing each feeder individually is faster than a simultaneous analysis of all feeders. However, the individual analysis method would not guarantee optimal, and in many cases accurate, solutions. Power quality as a performance measure for hosting capacity calculations, commonly studied in terms of harmonic distortion, is investigated in [13,14]. The model proposed in [13] explores the effects of harmonic distortion limits on hosting capacity under various active network management schemes, and authors in [14] investigate the impact of nondispatchable DGs on the harmonic distortion, and accordingly on grid hosting capacity. Optimal installation of DGs is derived in this work while preventing accumulated *h* order harmonic current from driving the harmonic voltage past acceptable limits.

Among the methods proposed to increase grid hosting capacity, active power management, power curtailment, and voltage control can be pointed out. A profit maximization strategy is developed in [15] for distribution utilities specializing in providing network access for third party DGs. The strategy informs infrastructure investment decisions by optimizing the profit from the acceptable hosting capacity. In addition, the active/reactive power curtailment strategy, specifically for voltage rise mitigation, has been demonstrated to produce beneficial results in the hosting capacity optimization problems in [16]. In [17], an active and reactive power control of the solar PV inverter to increase overall hosting capacity is explored. The studies in this work, however, are limited to only a few snapshots of demand and generation rather than a longer time horizon analysis. The impact of solar PV reactive power absorption on excessive voltage rise is inspected in [18] to assess DG performance. Multiple feed-in management strategies in order to increase the hosting capacity in a synthetic distribution system is studied in [19], benefiting from Monte Carlo simulations to derive general trends and to analyze specific grid, load, and DG architectures. A decentralized power control strategy is used in [20] to optimize grid hosting capacity by regulating the feeder voltage profiles. In a related study in [21], a hosting capacity optimization method is proposed to determine the optimal size and location of DGs using on-load tap changers (OLTC) and static Var compensators (SVC). The volt/Var control problem based for maximizing hosting capacity is modeled as a single-objective optimization problem in [22,23]. This model is extended to a multi-objective optimization problem in [24], in which a cuckoo search method is used to improve voltage profiles and reduce losses by optimizing DG allocation. The authors indicate two indices to measure quality improvement: voltage deviations from a reference value (which should be minimized) and voltage differences before and after DG integration (which should be maximized). The cuckoo search method is reported to outperform competing algorithms in efficiency in this particular problem. In [25], the impact of increasing solar PV units in residential neighborhoods is investigated and the hosting capacity is obtained in systems ranging from low voltage to medium voltage through a stochastic analysis framework. A C-type passive filter is used to optimize the hosting capacity while reducing harmonic distortions from DGs in [26]. In a related study, a variety of PV inverters are tested in [27] to find out how efficient the use of active and reactive power control strategies would be in increasing hosting capacity. However, it is concluded that the slow response time and switching restrictions of typical compensators prevent a fast and reliable control, which accordingly underscores the need for efficient voltage and reactive power control to achieve acceptable results when solving this problem. An optimization strategy for stabilizing nodal voltages and reducing system losses is employed in [28]. Bifurcation analysis is used to rank the nodal