Electrical Power and Energy Systems 105 (2019) 867–876

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Scalable enumeration approach for maximizing hosting capacity of distributed generation

Yuji Takenobu[a,*], Norihito Yasuda[b], Shin-ichi Minato[c], Yasuhiro Hayashi[a]

[a] Department of Advanced Science and Engineering, Waseda University, Tokyo 169-8555, Japan
[b] NTT Communication Science Laboratories, Nippon Telegraph and Telephone Corporation, Kyoto 619-0237, Japan
[c] Graduate School of Information Science and Technology, Hokkaido University, Sapporo 060-0808, Japan

ARTICLE INFO

Keywords:
Distributed generation
Network configuration
Second-order cone programming (SOCP)
Zero-suppressed binary decision diagram (ZDD)
ZDD vector (ZDDV)

ABSTRACT

At the stage of planning distributed generation (DG) for a distribution network, the network configuration is a key factor in increasing the DG hosting capacity. The determination of a configuration that maximizes the hosting capacity is a highly complex, nonlinear combinatorial optimization problem. No existing method can yield the global optimal solution for practical-scale networks. Therefore, this paper proposes a scalable optimization method. Specifically, the proposed method enumerates all optimal configurations while simultaneously considering optimal DG placement. The proposed method first optimizes the DG placement for possible partial networks using a second-order cone programming technique. Next, it enumerates possible combinations of the partial networks while avoiding a combinatorial explosion using a highly compressed data structure. Finally, it finds the optimal configurations by exploring solutions over the data structure. In experiments involving a large-scale network containing 235 switches, our enumeration method obtained 1.49×10^{18} global optimal configurations in 17.1 h. Another powerful feature of our method is that it enables distribution system operators to select the preferred optimal configuration interactively.

1. Introduction

The penetration of distributed generation (DG) resources (including photovoltaic and wind resources) into distribution networks is on the rise worldwide. This penetration has already resulted in several system operation issues, including voltage violations and the overloading of system equipment. Under these circumstances, current policies reinforce the distribution networks (e.g., new transformers or distribution lines) with a “fit and forget” approach on a case-by-case basis. However, this approach results in a high investment cost. It is desirable that as much DG as possible should be introduced into the distribution network without the need for reinforcements.

For increasing the DG hosting capacity, DG planning with a network reconfiguration is effective operation and planning. DG planning considers DG placement (locations and capacities) for the given DG connection requests or DG location candidates, and the network reconfiguration changes a network topology by specifying the switch on/off states. The optimization of both the DG placement and the configuration is a computationally hard task. This is because determination of the DG placement involves nonlinearity of the power flow and the number of configuration solution candidates increases exponentially with the order $O(2^n)$ as the number of switches n increases.

There are many papers that have developed approaches for increasing the DG hosting capacity. References [1–5] focus on the optimization of the DG placement. These studies are summarized in survey papers such as [6,7]. In addition to optimization of the DG placement, several researches also address the computational issues of optimizing the network configuration. Some of them apply approximate approaches such as particle swarm optimization [8] and genetic algorithms [9]. Since these metaheuristic approaches may become stuck in local minima, they provide no guarantee for the quality of the solution. To guarantee global optimality, Lueken et al. proposed a brute-force method [10] that calculates all possible configurations. Because their method relies on exhaustive enumeration, the applicable network size is limited. Recently, exact methods based on numerical programming called optimal power flow (OPF) have been proposed. Specifically, Ferreira et al. proposed the use of mixed integer linear programming (MILP) based on linearized power flow [11], and Capitanescu et al. formulated mixed integer nonlinear programming (MINLP) [12]. These approaches optimize the problem by using commercial solvers. However, even these methods suffer from scalability problems. In their experiments, the optimal solutions are obtained only for a small-sized

* Corresponding author.
E-mail address: nobutakeyuji@akane.waseda.jp (Y. Takenobu).

https://doi.org/10.1016/j.ijepes.2018.09.010
Received 29 March 2018; Received in revised form 3 July 2018; Accepted 8 September 2018

network, which is a 32-bus network with 37 switches [13]. It is our assertion that many MILP/MINLP solvers rely on the internal use of branch-and-bound methods. The size of a branch tree becomes massively large as the size of the distribution network increases, implying that obtaining optimal solutions using these methods is difficult for practical-scale networks (e.g., several hundreds of switches) [14,15].

This paper proposes a scalable optimization method. The key idea for providing scalability is to represent the huge solution search space in a compressed manner and then to find optimal solutions over the compressed search space. In addition to scalability, the proposed method has a powerful feature; it can obtain all possible optimal solutions. In general, with respect to the configuration optimization, multiple solutions become optimal or near optimal; in this situation, it is a natural requirement to provide multiple solutions for selecting preferred solutions interactively. Although conventional OPF-approaches yield one optimal solution, the proposed method can obtain all such optimal solutions on the basis of an enumeration approach.

The scalability of the conventional enumeration approach of [10] is limited to small-sized networks. The aim of the proposed enumeration approach is to handle larger networks. The proposed method extends an enumeration approach for optimizing configurations (specifically, the power loss minimization approach) developed by Inoue et al. [16]. The method can enumerate all feasible configurations by using a data structure called the zero-suppressed binary decision diagram (ZDD) [17], which enables us to represent a set of switch combinations (configurations) compactly. Then, the method obtains the optimal configuration by exploring the data structure. Since the data structure is compactly represented, the exploration of the solution also finishes in a short time. However, the method relies on a nontrivial assumption; it assumes that the power losses of root sections (i.e. a section adjacent to a feeding point) and nonroot sections can be calculated independently. As for the power loss, this assumption was practically reasonable. However, since the hosting capacity depends on the root and nonroot sections, we cannot assume such independence. For example, DG placement considering only nonroot sections may cause overloading at the root sections or voltage violations due to an unknown voltage rise at the root sections. To handle the interactions between the root and nonroot sections, we exploit the enhanced data structure of a ZDD, called a ZDD vector (ZDDV) [18]. The ZDDV can hold structures and values compactly and enables efficient numerical arithmetic operations between them to be performed. Using the ZDDV, we represent both the integrated structure of the root and nonroot sections and its hosting capacity. Then, we utilize the numerical arithmetic operations to find the optimal solutions.

The rest of this paper is organized as follows. Section 2 formulates the DG hosting capacity maximization problem, Section 3 outlines the features of the ZDDV, Section 4 describes the method for solving the DG hosting capacity maximization problem, Section 5 describes our experiments and results and Section 6 summarizes the paper.

2. DG hosting capacity maximization problem

This section formulates the DG hosting capacity maximization problem, which determines the switch states and DG placement (locations and capacities). To formulate this problem, we first describe a power flow model of a distribution system. The exact calculations for the power flow are described by complicated nonlinear equations. Thus, conventional methods approximate the power flow equations so that mathematical programming may be applied [11,19]. We also use a simple network model, introduced by Nara et al. [20]. The network model consists of feeding points, switches and line sections. For the i-th line section, the impedance $z_i = r_i + jx_i$, the current load at a particular time $I_{\ell,i}$, and the DG connection request value $I_{g,i}^{\max}$ are given. We assume that the section load and the DG capacity within a section are uniformly distributed within that section and that the power factor of the section's DG is 1.0.

2.1. Objective function

The aim of this problem is to maximize the overall amount of DG in a distribution system by determining the switch states and DG placement; we call the overall maximum DG capacity the maximum hosting capacity (MHC)

$$\mathrm{MHC} = \max \sum_{i=1}^{m} I_{g,i}, \tag{1}$$

where $I_{g,i}$ is the installed DG capacity within the i-th section and m is number of sections.

2.2. Constraints

2.2.1. Radial constraint

Let $S = \{s_1, \ldots, s_n\}$ denote a set of switches installed in the distribution network, and let the $X \subseteq S$ network configuration denote a set of closed switches. In general, networks are required to satisfy the radial constraint

$$X \text{ is a radial configuration.} \tag{2}$$

2.2.2. DG capacity limits

The installed DG capacity $I_{g,i}$ must be within the DG connection request value $I_{g,i}^{\max}$:

$$0 \leqslant I_{g,i} \leqslant I_{g,i}^{\max}, \quad i = 1, \ldots, m. \tag{3}$$

2.2.3. Current flow equations

For a tree included in a given radial configuration X, let $C_i(X)$ be all downstream line sections of i-th line section (including the i-th section), and let $N_i(X)$ be the downstream line sections adjacent to the i-th line section (excluding the i-th section). The load current $J_{\ell,i}$ and the DG current $J_{g,i}$ on the i-th line section are then given as follows:

$$J_{\ell,i} = J_{\ell,i}^{re} + jJ_{\ell,i}^{im} = \sum_{j \in C_i(X)} I_{\ell,j}, \quad i = 1, \ldots, m \tag{4}$$

$$J_{g,i} = \sum_{j \in C_i(X)} I_{g,j}, \quad i = 1, \ldots, m. \tag{5}$$

2.2.4. Voltage drop equations

The voltage drops between neighboring line sections are defined as

$$V_{\ell,i}^{re} - V_{\ell,j}^{re} = D_j^{re}, \quad i = 1, \ldots, m, \quad j \in N_i(X) \tag{6}$$

$$V_{\ell,i}^{im} - V_{\ell,j}^{im} = D_j^{im}, \quad i = 1, \ldots, m, \quad j \in N_i(X) \tag{7}$$

$$V_{\ell g,i}^{re} - V_{\ell g,j}^{re} = D_j^{re} - r_j \sum_{k \in N_j(X) \setminus \{j\}} \frac{J_{g,k}}{2}, \quad i = 1, \ldots, m, \quad j \in N_i(X) \tag{8}$$

$$V_{\ell g,i}^{im} - V_{\ell g,j}^{im} = D_j^{im} - x_j \sum_{k \in N_j(X) \setminus \{j\}} \frac{J_{g,k}}{2} \quad i = 1, \ldots, m, \quad j \in N_i(X) \tag{9}$$

where

$$D_i^{re} + jD_i^{im} = z_i \sum_{j \in N_i(X) \setminus \{i\}} \frac{J_{\ell,j}}{2}. \tag{10}$$

The equations in (6) and (7) indicate the voltage drops for the DG disconnected network. On the other hand, the equations in (8) and (9) indicate the voltage drops for the DG connected network. The voltage variables for the different load conditions are used in the next subsection.

2.2.5. Voltage magnitude limits

$$V_i^{\min 2} \leqslant V_{\ell,i}^{re2} + V_{\ell,i}^{im2} \leqslant V_i^{\max 2}, \quad i = 1, \ldots, m \tag{11}$$