Electric Power Systems Research 152 (2017) 36–47

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Load variations impact on optimal DG placement problem concerning energy loss reduction

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ARTICLE INFO

Article history:
Received 5 July 2016
Received in revised form 7 March 2017
Accepted 21 June 2017

Keywords:
Critical nodes
Energy loss reduction
Load variations
Optimal DG placement

ABSTRACT

The Optimal Distributed Generation Placement problem (ODGP) towards energy loss minimization depends basically on the network's layout and its load composition. Under load variations, different load compositions result, for each one of them, is highly possible to come up with a different optimal solution regarding the optimal siting and sizing of DG units. This paper examines the impact of these variations in order to verify how optimal solution should adapt to any load composition. A Local Particle Swarm Optimization Variant algorithm is proposed as the solution algorithm and numerous load composition snapshots for the IEEE-33 bus system are examined. Moreover, a methodology is proposed in order to highlight the critical nodes that prove to have an essential role to the solution. Finally, the possibility for the determination of a fixed solution with fixed installation nodes and constant power output that could yield near optimal energy loss reduction is examined.

1. Introduction

Incorporation of Distributed Generation (DG) has caused alterations to both the structure and infrastructure of the grid, especially to Distribution Networks (DNs). New challenges regarding the grid-integration of DG have been raised with respect to technical and operational issues that had to be faced through a novel approach [1–4]. On the one hand, these dispersed power units could affect traditional operational aspects of the DNs like the downstream power flow [5], and could cause power quality issues [6]. On the other hand, proper consideration and planning about the siting and sizing of such units could benefit the DN and the upstream grid in many ways. Such benefits are loss reduction [7], voltage improvement [8], reliability improvement [9] and CO_2 emission reduction [10] especially under the installation of Renewable Energy Sources (RESs). This latter approach, namely known as Optimal Distributed Generation Placement (ODGP) problem has attracted a lot of attention during the last two decades in order to offer a guideline towards efficient DG penetration planning.

One of the most common operational issues of DNs related to the ODGP problem refers to the investigation of the optimal siting and sizing of DG units for power loss minimization. This objective is either faced individually [11,12] or constitutes the main one in multi-objective approaches, highly prioritized by a weight factor [13,14]. The optimal solution of the ODGP problem is subject to the simultaneous optimization of the four involved variables [15,16], i.e., the index of the DG hosting nodes, the number and the capacity of the individual DG units, as well as the aggregated DG capacity to be penetrated in the DN. Most of the literature yield biased solutions due to the fact that one or more of the aforementioned variables are predefined. Therefore, some approaches propose a two-stage solution of the problem where the siting part of the problem is firstly solved and then the optimal capacity of the DG units is examined [17,18]. Other studies examine the optimal installation of a small predefined number of DG units [19,20] or investigate how a specific DG capacity with fixed DG units could be optimally allocated [21]. The methods which incorporate either a consecutive solution or a partially predefined input, could produce biased results, different from optimal ones. Moreover, many solution algorithms have been proposed to deal with the problem like analytical methods [22], numerical methods [23] and heuristics [24,25], e.g. genetic algorithms, Particle Swarm Optimization algorithms and differential evolution methods.

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http://dx.doi.org/10.1016/j.epsr.2017.06.016
0378-7796/

The main disadvantage of most of the existing methodologies relies on the fact that the solution provided refers to a specific snapshot of the DN operation with a fixed load composition. The solution for the ODGP problem depends on the layout of the DN and its load composition. Thus, under load variations, the load composition is accordingly varied, and the solution is expected to alter as well. Therefore, the question raised in such cases is the determination of one representative solution, among all possible, that could be considered optimal regardless the DN load composition.

The impact of DG units on energy losses will depend on the specific characteristics of the network, such as demand profile, topology, as well as the relative location of the generators and whether their output is firm or variable. Incorporating these complexities into an optimization framework for energy loss minimization is a challenge that has only been partially addressed by a few studies [26]. In [27] the analysis regarding load and DG power output variations relies on uniformly distributed loads while these variations refer to a typical daily pattern for both. Moreover, only the optimal siting of DG units is examined, and one DG unit is considered for installation. In [28] the case of one wind power unit under both power output and load demand variations is examined. The analysis yields the optimal node for the wind power unit installation by considering a sequential analysis with only one candidate node for DG installation at a time and concludes that subject to load variations, the optimal location is different when compared to the operational snapshot. In [29] a probabilistic technique is proposed for optimally allocating different types of DG technologies. The technique is based on generating a probabilistic generation-load model. Beta and Rayleigh Probability Density Functions (PDFs) are used for simulating solar irradiance and wind speed uncertainty, respectively, while IEEE-RTS for the load profile. However, the positions of the DGs are predetermined, as the number of DGs as well. Other approaches incorporating load or DG power variations, as in [30], may provide biased solutions since the installation nodes are predetermined. Furthermore, the analysis in [31] concludes that the power analysis of one load snapshot is not necessarily adequate for the overall operation of the DN. Rotaru et al. [32] propose a two-stage method of optimal siting and sizing of DGs. Finally, Shaaban et al. in [33], propose a method to address and evaluate the economic benefits of Renewable DGs when applied to DNs, but the candidate buses are predetermined and the number of DGs for each type is limited and predefined.

In this paper, the ODGP problem subject to load variations is considered as a power oriented problem regarding the net power demand and/or generation of the optimal nodes towards energy loss minimization. The operational snapshot with the average load composition of the DN is considered as the base case scenario and numerous different operational states with altered load compositions are stochastically generated under a uniform distribution with specific deviations. These deviations are properly chosen in order to describe either smooth transitions across the DN load curve, aiming to simulate load alterations concerning daily or weekly load profiles, or more intense load variations that could describe monthly and seasonal load profiles. Next, each stochastically generated scenario is treated as an individual sub-problem, where the same analysis is applied and the ODGP problem is solved with a Local PSO Variant (LPSOV) algorithm. The above scenarios are considered to compile most of the possible operational states of the DN during a year. Thus, the respective solutions for these scenarios constitute the optimal siting and sizing for the DG units that could yield minimum annual energy losses. Although each load composition delivers an individual optimal solution, the analysis is extended to investigate whether a fixed solution for both the installation points and the DG units capacity could yield a near-optimal energy loss reduction. The contribution of this work in power system planning is twofold; firstly, the identification of critical DN nodes to host DG units, and secondly the determination of the optimal capacities of the latter when considered with fixed power output, towards energy loss minimization.

This paper is organized as follows: in Section 2 the problem formulation along with the LPSOV algorithm and the examined DN are presented. In Section 3, the conceptual justification and mathematical formulation regarding the load variations are analyzed. In Section 4, the results regarding the examined scenarios are presented and discussed while Section 5 is devoted to conclusions.

2. Proposed methodology

2.1. Problem formulation

The precise computation of energy loss in DNs presumes the availability of real time-series data regarding the actual power flows in all branches. The operators of modern DNs usually keep a measurement log on a 15-min basis, which means that they can assess load variations adequately. Moreover, when a rough estimation is required, the mean load values could be utilized to compute the energy loss for a given period. The accuracy of this estimation depends on the divergence of each node's load variation from the respective considered mean value. The ODGP problem is highly affected by the initial state of the DN in terms of both its topology and load composition. Therefore, under a fixed DN layout, e.g., radial structure with no tie-switch activation, each different snapshot of the DN operational status with altered load composition requires a different solution for the installation nodes and the power output of DG units towards loss minimization. Hence, all different snapshots with altered load composition are expected to yield different solutions for the ODGP problem. A generic objective function which aims at minimizing the energy loss in DNs, taking into account the sum of the sequential snapshots of the network with fixed load compositions, is presented in (1).

$$F_{\text{loss}} = \min \sum_{\Delta t=1}^{k} \sum_{\substack{i,j=1\\ i\neq j}}^{n_l} g_{i,j}\left[(V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_i-\theta_j)\right] \tag{1}$$

where

F_{loss} is the objective function to be minimized,
k is the number of different sequential snapshots with fixed load composition that constitute the time period under study,
V_i and V_j are the voltage magnitudes of nodes i and j,
θ_i and θ_j are the voltage angles of nodes i and j,
$g_{i,j}$ is the conductance between nodes i and j,
n_l is the total number of branches in the network.

The problem expressed by (1) is subject to the operational constraints:

$$V_i^{\min} \le \quad V_i \le V_i^{\max} \tag{2}$$

$$I_b \le I_b^{\max} \tag{3}$$

where $V_i^{\min}$ and $V_i^{\max}$ are the voltage of node i, and $I_b^{\max}$ is the maximum allowed RMS current of branch b.

The constraints in (2) and (3) along with the conventional constraints regarding the power flow equations are embedded in the objective function as penalty terms [12,34], to reduce the computational burden and facilitate the solution process. A generic penalty function is:

$$P(x) = f(x) + \Omega(x) \tag{4}$$

$$\Omega(x) = \rho\{g^2(x) + [\max(0, h(x))]^2\} \tag{5}$$