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A practical eco-environmental distribution network planning model including fuel cells and non-renewable distributed energy resources

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ABSTRACT

This paper presents a long-term dynamic multi-objective planning model for distribution network expansion along with distributed energy options. The proposed model optimizes two objectives, namely costs and emissions and determines the optimal schemes of sizing, placement and specially the dynamics (i.e., timing) of investments on distributed generation units and network reinforcements over the planning period. An efficient two-stage heuristic method is proposed to solve the formulated planning problem. The effectiveness of the proposed model is demonstrated by applying it to a distribution network and comparing the simulation results with other methods and models.

1. Introduction

Distributed Generation (DG) is an electric power source connected directly to the distribution network. Different factors like electricity market liberalization, system reliability enhancement [1] and efforts to lower the global warming have made them more interesting for electricity sector. DG units are owned either by distribution network operators (DNOs) [2] or by non-DNO entities [3]. In either case, DG may offer DNOs more diverse, flexible, and secure options for managing their electricity systems to meet the load growth as an alternative to traditional network reinforcement. In recent years, many approaches have been proposed addressing DG planning and integration of them into distribution systems. The literature suggests a wide range of objectives, such as investment deferral in network capacity [4] and active loss reduction [5], reactive loss reduction [6,7], reliability improvement [8], reducing the cost of energy required for serving the customers [8], increasing the incentives received by distribution network owners for using DGs [6], reducing the cost of energy not supplied and emission reduction [9,5]. These studies have considered a variety of technical issues including voltage profile [4,7], capacity limits of conductors [4,7], substation capacity [4,10], three phase and single phase to ground short circuit, and load modeling [7]. The reported models for DG planning can generally be divided into two major categories: static and dynamic models. In static models, investment decisions are implemented in the first year of the planning horizon [8]. In this category, the models are single or multi-objectives. The DG planning can be formulated as a single or multi-objective optimization problem. If only a single objective is of interest for the planner, then it is formulated as a single-objective problem. When many objectives are of interest, the problem is either translated to a single-objective problem (usually adding objectives into a single measure of performance [4]), or formulated as “true” multi-objective problem using Pareto optimality concept [10,9]. In static models, [11,12] consider network reinforcement along with DG investment. The value of multi-objective problem formulation of DG planning is that the objectives are usually in conflict or they cannot be easily converted into a single-objective problem [13]. It should also be noted that using the multi-objective methods can provide a decision making support tool for the planner that is able to justify its choices clearly and consistently [14]. In this paper, a planning model for DG-planning problem is formulated which is not only multi-objective but also it is dynamic and a two-stage algorithm is proposed to solve the problem. In the first stage, the set of Pareto optimal solutions is found using a new hybrid Immune-GA method, and in the second stage, the best solution is chosen using a fuzzy satisfying technique. The model aims at all three aspects of

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placement, sizing and timing of DG investment simultaneously, while also considering distribution feeder and transformer reinforcements. The main contributions of this paper are:

1. A multi-objective dynamic DG-planning model with the consideration of network reinforcements is proposed.
2. The proposed model is solved using a new efficient heuristic method which dominates the other heuristic methods.

This paper is set out as follows: Section 2 presents problem formulation, Section 3 sets out the proposed solution method for solving the problem. The application of the proposed model and the simulation results are presented in Section 4 and finally, Section 5 summarizes the findings of this work.

2. Problem formulation

The multi-objective DG-planning formulation is presented in this section. The decision variables are the number of DG units from each specific technology, to be installed in each bus in each year, i.e., ξ_{it}^{dg}; binary investment decision in feeder ℓ in the year t, i.e. γ_t^ℓ which can be 0 or 1, and finally the number of new installed transformers in the year t, i.e. ψ_t^{tr}. The assumptions used in problem formulation, constraints and the objective functions are explained next.

2.1. Assumptions

The following assumptions are employed in problem formulation:

- Connection of a DG unit to a bus is modeled as a negative PQ load [11]. It should be noted that this assumption is not valid for some DG technologies like wind turbines which have stochastic behaviors.
- All of the investments are done at the beginning of each year.
- The daily load variations over the long-term are modeled as a load duration curve with N_{dl} demand levels. Assuming a base load of $P_{i\text{base}}^{D}$, a Demand Level Factor of DLF_{dl} and a demand growth rate of α, the demand in bus i, in year t and in demand level dl can be calculated as:

$$\begin{aligned} P_{i,t,\text{dl}}^{\text{D}} &= P_{i,\text{base}}^{D} \times \text{DLF}_{\text{dl}} \times (1+\alpha)^t \\ Q_{i,t,\text{dl}}^{\text{D}} &= Q_{i,\text{base}}^{D} \times \text{DLF}_{\text{dl}} \times (1+\alpha)^t \end{aligned} \tag{1}$$

- The price of energy purchased from the grid is competitively determined in a liberalized market environment and thus, it is not constant during different demand levels. Estimating the variations of electricity market prices in the long-term is beyond the scope of this paper – see [15] for some insights. Without loosing generality, it is assumed that the electricity price at each demand level can be determined as $\rho \times \text{PLF}_{\text{dl}}$, where the base price (i.e. ρ), and the Price Level Factors (i.e. PLF_{dl}), are known; the potential economic risks of this assumption are not analyzed in this paper.
- The DNO is assumed to own and operate the network and thus having access to all network information. Also, network reinforcement in the form of adding new feeders or transformers is considered by the DNO along with adding DG units as an integrated framework.

A nomenclature of symbols and abbreviations is defined at the end of the paper.

2.2. Constraints

2.2.1. Power flow constraints

The power flow equations that should be satisfied for each configuration and demand level are:

$$\begin{aligned} P_{i,t,\text{dl}}^{\text{net}} &= -P_{i,t,\text{dl}}^{\text{D}} + \sum_{\text{dg}} P_{i,t,\text{dl}}^{\text{dg}} \\ Q_{i,t,\text{dl}}^{\text{net}} &= -Q_{i,t,\text{dl}}^{\text{D}} + \sum_{\text{dg}} Q_{i,t,\text{dl}}^{\text{dg}} \\ P_{i,t,\text{dl}}^{\text{net}} &= V_{i,t,\text{dl}} \textstyle\sum_{j=1}^{N_b} Y_{ij}^t V_{j,t,\text{dl}} \cos\left(\delta_{i,t,\text{dl}} - \delta_{j,t,\text{dl}} - \theta_{ij}^t\right) \\ Q_{i,t,\text{dl}}^{\text{net}} &= V_{i,t,\text{dl}} \textstyle\sum_{j=1}^{N_b} Y_{ij}^t V_{j,t,\text{dl}} \sin\left(\delta_{i,t,\text{dl}} - \delta_{j,t,\text{dl}} - \theta_{ij}^t\right) \end{aligned} \tag{2}$$

2.2.2. Operating limits of DG units

The DG units should be operated considering the limits of their primary resources, i.e.:

$$P_{i,t,\text{dl}}^{\text{dg}} \le \sum_{\acute{t}=1}^{t} \xi_{i,\acute{t}}^{\text{dg}} \times \overline{P}_{\text{lim}}^{\text{dg}} \tag{3}$$

The power factor of DG unit is kept constant [6] in all demand levels, as follows:

$$\cos\varphi^{\text{dg}} = \frac{P_{i,t,\text{dl}}^{\text{dg}}}{\sqrt{\left(P_{i,t,\text{dl}}^{\text{dg}}\right)^2 + \left(Q_{i,t,\text{dl}}^{\text{dg}}\right)^2}} = \text{const.} \tag{4}$$

2.2.3. Voltage profile

The voltage magnitude of each bus should be kept between the operation limits, as follows:

$$V^{\min} \le V_{j,t,\text{dl}} \le V^{\max} \tag{5}$$

2.2.4. Capacity limit of feeders and substation

To maintain the security of the feeders and the substation, the flow of current/energy passing throw them should be kept below the feeders/substation capacity limit as follows:

$$I_{\ell,t,\text{dl}} \le \overline{I}_\ell + \text{Cap}_\ell \times \sum_{\acute{t}=1}^{t} \gamma_{\acute{t}}^{\ell} \tag{6}$$

where $\text{Cap}_\ell \times \sum_{\acute{t}=1}^{t} \gamma_{\acute{t}}^{\ell}$ represents the added capacity of feeder due to the investments made until year t.

For substation capacity constraint, also, the same philosophy holds, as follows:

$$S_{t,\text{dl}}^{\text{grid}} \le \overline{S}_{\text{tr}} + \text{Cap}_{\text{tr}} \times \sum_{\acute{t}=1}^{t} \psi_{\acute{t}}^{\text{tr}} \tag{7}$$

where $\text{Cap}_{\text{tr}} \times \sum_{\acute{t}=1}^{t} \psi_{\acute{t}}^{\text{tr}}$ represents the added capacity of substation resulting from adding new transformers until year t.

2.3. Objective functions

The proposed model minimizes two objective functions, namely, total costs and total emissions of the DG investment problem, as follows:

$$\begin{aligned} &\min\{\text{OF}_1, \text{OF}_2\} \\ &\text{subject to}: \\ &(1) \rightarrow (7) \end{aligned}$$

The objective functions are formulated next.