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Hybrid simulated annealing and mixed integer linear programming algorithm for optimal planning of radial distribution networks with distributed generation

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ABSTRACT

This paper presents a hybrid simulated annealing (SA) and mixed integer linear programming (MILP) approach for static expansion planning of radial distribution networks with distributed generators (DGs). The expansion planning problem is first modeled as MILP optimization problem with the goal of minimizing the investment cost, cost of losses, cost of customer interruptions due to failures at the branches and at DGs and the cost of lost DG production due to failures at branches. In order to reduce the complexity of planning problems the decomposition of the original problem is proposed into a number of sequences of sub-problems (local networks) that are solved using the MILP model. The decomposition and solution process is iteratively guided and controlled by the proposed SA algorithm that employs the proper intensification and diversification mechanism to obtain the minimum total cost solution.

1. Introduction

Distribution expansion planning is a hard combinatorial optimization problem with a long history of contributions for improved solutions [1–3]. One of the major characteristics of approaches proposed so far is whether they consider a single planning period or multi planning periods. The majority of models and approaches proposed for solving real-size multi-period planning problems produces a solution that is, among others, highly dependent on the effectiveness of static models integrated in the multi-period algorithm [4]. The models proposed for solving single-period (static) planning problems could be categorized as follows: mathematical programming based models, heuristic models and meta-heuristic models.

Mathematical programming models, which can guarantee the optimality of the obtained solutions, are mostly based on mixed integer linear programming (MILP) [1,5–10]. In [7] the MILP formulation of planning problems based on mixed integer conic programming and polyhedral relaxation is presented. The proposed approach enables accurate modeling of planning problems in which investment cost and cost of losses are considered (minimized). In [8] the MILP model is designed to minimize the investment and maintenance cost and cost of losses. The pool of solutions is obtained by varying relative optimality gap tolerance in the course of solving the MILP optimization problem and for each of them the cost of interruptions due to failures at branches is determined. The solution with minimum total cost becomes the best solution. The influence of distributed generators (DGs) at the planning process is discussed in [9] where the MILP model is presented with the goal of finding the solution with minimum investment and maintenance cost in the presence of DGs. In [10] the MILP model is designed to determine optimal type, size and allocation of DGs in radial distribution systems taking into account installation cost of different types of DGs and cost of energy supplied by the DGs and by the distribution system. Although continuous improvements are made, due to significant computational complexity the MILP models are not capable for solving large planning problems in reasonable time. Heuristic algorithms, [11–13], although capable of finding "good" solutions (local optima) for real-size planning problems using relatively modest computational resources, do not guarantee the optimality of the obtained solutions. In order to improve the quality of heuristic methods, especially to overcome local optima, a numerous meta-heuristic algorithms are proposed [14–18]. The model based on simulated annealing (SA) technique that finds a solution with minimum investment cost, cost of losses, and cost of interruptions due to failures at branches in passive radial distribution networks is presented in [16]. In [17] a combination of optimal power flow (OPF) and genetic algorithm is used to find the network development plan along with the sizes and sites of DGs that ensures

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minimal investment and operational cost and cost of interruptions due to failures at branches. A similar problem, where construction of tie-lines for improving reliability is considered, is handled in [18] by employing the modified particle swarm optimization technique. Although meta-heuristic algorithms may produce a better solution than heuristic ones, the quality of the obtained solution is uncertain, i.e. there is no guarantee of exactly how good the obtained solution is. A comprehensive survey of the above mentioned optimization approaches (heuristic, meta-heuristic, MILP), along with the analysis of their advantages and disadvantages, that have been applied in the other research areas in power systems could be found in [19–21].

This paper proposes a new MILP model for static expansion planning of radial distribution networks with DGs that minimizes the investment cost, cost of losses, cost of customer interruptions due to failures at branches and at DGs and the cost of lost DG production due to failures at branches while taking into account a set of operational constraints (thermal constraints, voltage constraints, radiality constraints). In order to reduce the complexity of planning problems, which is significantly increased by taking into account failures at branches and especially at DGs, the decomposition algorithm based on SA technique is proposed. In the first step, the original problem is decomposed into a number of sub-problems (sub-networks/local networks) by employing the local network concept [22,23]. Each sub-problem is solved by applying the proposed MILP model and thus the initial solution of the original problem is obtained. This solution is further iteratively modified using the proposed simulated annealing algorithm that employs the proper intensification and diversification mechanism to search for the minimum cost solution. The obtained numerical results show that the proposed MILP model and the proposed decomposition approach (SA-MILP) can produce high quality solutions for static planning problems in radial distribution networks with DGs. The results also show that failures at DGs may have noticeable influence on the selection of the best expansion plan.

2. Problem formulation

The goal of a static expansion planning of distribution networks with DGs can be stated as follows: determine a set of network enhancements (upgrades and/or new constructions) that meets the forecasted demand, forecasted DG generation and the set of constraints (voltage constraints, thermal constraints, radiality constraints) so that the decision maker's planning goals are fulfilled in the considered planning period. Planning goals are usually expressed in monetary units [3], and thus the decision maker's goal becomes the minimization of total present worth cost. That is, the objective function (OF) of the static planning problem can be expressed as follows:

$$\mathrm{OF} = C_{\mathrm{inv}} + \sum_{i=1}^{\mathrm{TP}} \frac{1}{(1+d)^i} \times (C_{\mathrm{loss}} + C_{\mathrm{rel}}^{\mathrm{load}} + C_{\mathrm{rel}}^{\mathrm{DG}}), \tag{1}$$

where C_{inv} is the investment cost, C_{loss} is the annual cost of losses, $C_{\mathrm{rel}}^{\mathrm{load}}$ is the annual cost of customer interruptions due to failures at branches and at DGs, $C_{\mathrm{rel}}^{\mathrm{DG}}$ is the annual production lost cost of DGs due to failures at branches, TP is the considered planning period, and d is the discount rate. It should be noted that the static planning approach assumes that annual costs in (1) are the same in each year of the considered planning period (TP).

The investment cost (C_{inv}) appears in the initial year of the considered planning period and consists of the cost of constructing new elements and/or the cost of reinforcing/replacing the existing elements in the network. A linear approximation of cost of losses (C_{loss}) is used in this paper that enables accurate calculation of losses in MILP models without the inclusion of additional integer variables, which were required in the previously used approximations [5,8]. The proposed approximation is presented in Appendix A. The cost of supply interruptions $\left(C_{\mathrm{rel}}^{\mathrm{load}}\right)$ consists of the cost of unsupplied energy due to failures at branches and at DGs, which could differ for different categories (types) of customers. In radial networks there are no alternative supply routes and the outage of a branch interrupts the delivery to all consumers supplied through this branch. Since island operations of DGs are not approved by regulations in many countries (including the authors') those consumers will be without supply until the fault is repaired. Furthermore, failures at DGs in radial networks could cause a portion of customers (loads) having to be disconnected to prevent overloading of branches (feeders). Those customers will be without supply until the fault at a DG is repaired. The total cost caused by branch failures will be increased by the production lost cost of the DGs $\left(C_{\mathrm{rel}}^{\mathrm{load}}\right)$ since a generator is set out of operation at each branch failure disconnecting it from the source node.

As constraints, the bus voltage and the feeder current should be maintained within standard bounds and the network should be in radial operating state with non-island operation of DGs. Since in deregulated power systems DGs are often investor owned it is assumed here that their locations and sizes are known.

The above described planning problem is first modeled as a MILP optimization problem, as presented in Section 3.1. The decomposition approach based on the SA technique, the proposed MILP model, the branch-exchange technique and the local network concept is presented in Section 3.2.

3. Solution approach

3.1. Mixed integer linear programming model

The MILP model for solving static planning problem in radial distribution networks with DGs is designed as follows:

a) Objective function

$$\begin{aligned}
\min z = {} & \sum_{a\in M_E}\sum_{b\in SS_a} c_{a,b}^{inv} \times L_a \times (w_{a,b} + w'_{a,b}) + \sum_{a\in M_F}\sum_{b\in SS_a} c_{a,b}^{inv} \times L_a \times (w_{a,b} + w'_{a,b}) + \\
& + \sum_{i=1}^{TP} \frac{1}{(1+d)^i} \times \left\{ \sum_{a\in(M_E\cup M_F)} \sum_{b\in \underline{SS}_a} L_a \times \left(\sum_{ns=1}^{ns_{a,b}} (x_{a,b,ns} + x'_{a,b,ns}) \times KLoss_{a,b,ns} \right) + \right. \\
& \quad + \sum_{a\in(M_E\cup M_F)} \sum_{b\in \underline{SS}_a} (x_{a,b}^{f} + x_{a,b}^{\prime f}) \times K_{ENS} \times \lambda_a \times d_a \times c^{rel\,base} + \\
& \quad + \sum_{g=1}^{n_{DG}} \sum_{n\in N_{TOT}} (1 - y_{n,g}) \times K_{ENS} \times \lambda_g \times d_g \times D_n \times c_n^{rel} + \\
& \quad \left. + \sum_{m\in N_{DG}} \sum_{a\in(M_E\cup M_F)} \sum_{b\in \underline{SS}_a} (x_{a,b,m}^{DG} + x_{a,b,m}^{\prime DG}) \times K_{DG} \times DG_m \times \lambda_a \times d_a \times c_m^{DG} \right\}
\end{aligned} \tag{2}$$

The first term in the objective function (2) describes the cost of upgrading existing branches while the second term describes the cost of constructing new branches. The third term describes the present worth cost of power losses. This cost is modeled by using a number of linear segments, as presented in Appendix A. The fourth term along with relations (12)–(13) describes the present worth cost of undelivered energy due to failures at branches. The present worth cost of undelivered energy due to failures at DGs is given by the fifth term in (2) along with relations (14)–(18). The lost production cost of DGs due to faults at branches is described by the sixth term in (2) and relations (20)–(23).