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Multi-objective planning of electrical distribution systems using dynamic programming

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ABSTRACT

This paper presents a novel dynamic programming approach for multi-objective planning of electrical distribution systems. In this planning, the optimal feeder routes and branch conductor sizes of a distribution system are determined by simultaneous optimization of cost and reliability. The multiple planning objectives are minimization of: (i) installation and operational cost, and (ii) interruption cost. The first objective function consists of the installation cost of new feeder branches and substations, maintenance cost of the existing and new feeder branches, and the cost of energy losses. The second objective function measures the reliability of the distribution network in terms of the associated interruption costs for all the branches, which includes the cost of non-delivered energy, cost of repair, and the customer damage cost due to interruptions. A dynamic programming based planning algorithm for optimization of the feeder routes and branch conductor sizes is proposed. A set of Pareto solutions is obtained using a weighted aggregation of the two objectives with different weight settings. The proposed approach is evaluated on 21-, 54-, and 100-node distribution systems. The simulation test results are analyzed with various case studies and are compared with those of two existing planning approaches based on multi-objective evolutionary algorithm.

1. Introduction

Electric power distribution system planning is an important technology for power utilities in the deregulated power market [1,2]. A typical distribution system planning is broadly categorized either as a *static* or an *expansion* planning [1]. The static planning is a one-step planning of a new network, whereas an expansion planning is adopted to plan a network taking the load growth at the existing nodes and/or inclusion of additional load nodes. An expansion planning can be of single stage for single horizon year or multi-stage, i.e., stage-by-stage expansion. A proper planning of a distribution system not only saves expenditure for the utilities but also helps to meet customer satisfaction, which is very important in the competitive power market. A lot of computer-based distribution systems planning approaches are reported during the past three decades. State-of-the-art reviews of the reported works can be found in [3,4]. The distribution system planning is essentially an optimization process to obtain a number of planning/design variables such as: (i) size and location of distribution substation, (ii) number of feeders and their routes, and (iii) branch conductor sizes. The planning objectives include minimization of the installation cost of new facilities (substations/feeders/branches), cost of capacity addition of existing facilities, maintenance cost of the feeders and network power loss, and maximization of the network reliability. This optimization is also subject to some constraints, such as substation/feeder capacity limit, node voltage deviation limit, and network radiality.

In the early works [3–5], the planning model is formulated with one objective, i.e., minimization of installation cost and the cost of energy losses. The network reliability, an important aspect in the competitive power market, is also considered as another objective [6–29]. The network reliability is maximized by optimizing different reliability objective functions, such as total (cost of) non-delivered energy [6–13,24–28], customer outage cost [14], customer interruption cost [15,16], and contingency-load-loss index [29]. Two approaches have been used for optimizing the cost and reliability. In the first approach [6–16], both objectives are aggregated to obtain a single solution, while the second approach [17–29] takes the conflicting natures of the cost and reliability into account by simultaneous optimization of the two objectives to obtain a set of non-dominated solutions, called Pareto solutions [19,20] and a decision maker or the planning engineer selects one solution for implementation.

The main challenge in this planning is to devise a solution strategy as the objective functions are typically nonlinear, non-convex,

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non-differentiable with discrete and continuous decision variables. The difficulty increases with higher dimensions that depend on the number of nodes in the network. The reported solution strategies fall into two categories: (i) deterministic algorithms and (ii) heuristics-based algorithms. The deterministic algorithms are based on mathematical optimization technique. They can always produce same output for a given input. The heuristics-based algorithm can produce an acceptable solution to a problem in many practical scenarios, but there is no formal proof of its optimality. The deterministic algorithms that have been used for this problem are: nonlinear mixed integer programming [7], dynamic programming [6,8], nonlinear programming [9,10], Benders' decomposition [17,18], etc. Most of the heuristics-based algortithms applied to this problem are based on the evolutionary algorithms (EAs), such as genetic algorithm (GA) [12–16,19–24], tabu search (TS) [25,26], artificial immune system (AIS) [27], particle swarm optimization (PSO) [28,29], and honey bee mating optimization [30].

The evolutionary computation techniques are used as solution strategies in most of the Pareto-based multi-objective planning approaches [19–30] due to their multi-point search capability, which helps to obtain a set of non-dominated solutions in a single run. However, the major drawback of a multi-objective evolutionary algorithm (MOEA) is that the convergence is not always guaranteed. On the contrary, the deterministic algorithms are well known for their good convergence characteristics. Till date, few works [17,18] have reported the use of deterministic algorithms for simultaneous optimization of multiple objectives to obtain a set of non-dominated solutions. In [17], a two-step approach based on linear programming for optimization of continuous variables followed by integer programming for optimization of integer variables has been used. The formulation approximates the quadratic cost function due to energy losses as a linear function and solves it by linear programming. In [18], the mixed-integer programming (MIP) is used with commercial MIP-solver GAMS. The branch conductor size optimization has not been considered in both the approaches in view of both cost and reliability objectives as in some MOEA-based works [20,28]. There is another powerful deterministic algorithm, i.e., the dynamic programming, which can deal with this type of objective functions efficiently. Although, it is used in [6,8], none of the two approaches deals with simultaneous optimization of the objective functions. Moreover, it is reported in [8] that the computation time of GAMS is reasonably higher than that of dynamic programming for the same distribution system planning problem.

Motivated by all these issues, an attempt is made to investigate the use of dynamic programming for simultaneous optimization of the objective functions in a distribution system planning problem. The two objective functions of the proposed multi-objective planning model are formulated as: (i) *total installation and operational cost* and (ii) *total interruption cost*. The total installation and operational cost is the sum of the total installation costs of new facilities (substations/feeders/branches) and incremental capacity addition of the existing facilities, annual maintenance cost, and the discounted present value of the cost of energy losses. The second objective is the minimization of the total cost associated with the interruptions in all the branches and it includes three components, i.e., cost of non-delivered energy, cost of fault repair/maintenance, and customer damage cost due to interruptions. The first two components are utilities' cost due to faults and the last component is the customer cost due to interruptions. The last component, a measure of customer dissatisfaction, is very important in competitive markets. The solution strategy proposed in this work is based on dynamic programming for optimization of the feeder routes and branch conductor sizes. As the cost and reliability conflict with each other, a set of Pareto solutions is obtained using weighted aggregation of the objectives with different weight settings. Each weight combination yields one solution. The proposed approach is validated on three systems, i.e., 21-, 54-, and 100-node distribution systems, and on both static as well as expansion planning problems. The results are analyzed, with different case studies, and compared with the results of two MOEA-based planning approaches [20,28].

The key contributions of this paper are:

- A multi-objective planning algorithm using dynamic programming is proposed to determine the optimal feeder routes and branch conductor sizes with simultaneous optimization of cost and reliability.
- This planning algorithm is applicable for both static and expansion planning of distribution systems. It can also be used for the planning of both single and multi-feeder networks.
- An empirical simulation study is carried out to show the advantages of the dynamic programming based conductor size optimization over the conductor size selection. A qualitative and quantitative performance comparison between the proposed approach and two other previously reported MOEA-based approaches is provided to bring out the relative merits and demerits.

The organization of the paper is as follows. The modeling of distribution systems is briefly discussed in Section 2. The multi-objective planning model for electrical distribution systems and the proposed multi-objective dynamic programming approach are given in Sections 3 and 4, respectively. The simulation results are presented in Section 5. Section 6 concludes the paper. A list of symbols used in this paper is provided in the Appendix A.

2. Distribution system modeling

A typical distribution system consists of various components, such as substation, feeder, and load. This section provides the modeling of each component of a distribution network in the context of proposed planning approach. It is to be noted that this work deals with planning of primary distribution systems, which act as a liaison between transmission system and secondary distribution systems.

2.1. Substation modeling

A substation is the source of a distribution network. Sometimes, a distribution network is fed from two different substations. However, in this planning approach, this case is not considered. A substation consists of primary distribution transformers, switchgears, and several switching and protective equipments. In addition, a substation may be equipped with voltage regulators and shunt capacitors banks. In distribution system planning, a substation modeling basically includes the determination of the optimal size and site of a substation [1,2]. Since the location of a substation involves several social and political issues, most of the planning approaches do not include this as an optimization variable. Thus, in this planning approach, the optimal size of the substation located at a specified site is determined in static planning. For expansion planning, the capacity addition required to meet the additional load demand is determined. This is done by optimizing the installation cost of the substation and/or the cost of capacity addition of the existing substation. Total cost of a substation installation and/or capacity addition typically includes the cost of installation and/or capacity addition of substation switchgear, protective and metering arrangements, switching arrangements and installation