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A multistage framework for reliability-based distribution expansion planning considering distributed generations by a self-adaptive global-based harmony search algorithm

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ABSTRACT

In this paper, the authors present a new multistage framework for reliability-based Distribution Expansion Planning (DEP) in which expansion options are a reinforcement and/or installation of substations, feeders, and Distributed Generations (DGs). The proposed framework takes into account not only costs associated with investment, maintenance, and operation, but also expected customer interruption cost in the optimization as four problem objectives. At the same time, operational restrictions, Kirchhoff's laws, radial structure limitation, voltage limits, and capital expenditure budget restriction are considered as problem constraints. The proposed model is a non-convex optimization problem having a non-linear, mixed-integer nature. Hence, a hybrid Self-adaptive Global-based Harmony Search Algorithm (SGHSA) and Optimal Power Flow (OPF) were used and followed by a fuzzy satisfying method in order to obtain the final optimal solution. The SGHSA is a recently developed optimization algorithm which imitates the music improvisation process. In this process, the harmonists improvise their instrument pitches, searching for the perfect state of harmony. The planning methodology was demonstrated on the 27-node, 13.8-kV test system in order to demonstrate the feasibility and capability of the proposed model. Simulation results illustrated the sufficiency and profitableness of the newly developed framework, when compared with other methods.

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1. Introduction

1.1. Background and motivation

Distribution Expansion Planning (DEP) is one of main tasks of distribution utilities to meet both electricity demand growth at the lowest cost and customers' reliability requirements at an acceptable level [1,2]. The DEP problem determines location, size, and time of the reinforcement and/or installation of electric distribution network equipment. In general, the DEP problem can be classified as static or multistage planning. Static DEP problem considers only one planning horizon and computes optimal location and size of the network equipment [3,4]. In multistage DEP problem, the planning horizon is divided into several stages to determine optimal location, size, and time of the network equipment [5–9]. Traditionally, the DEP models are concentrated on minimizing the investment cost subject to technical and operational constraints over a planning horizon [8]. In modern distribution systems, however, restructuring has changed structures of operation and planning of distribution networks. With this regards, the main purpose of new created entities, such as Distribution Network Operators (DNOs) and Distribution Companies (DisCos), is to maximize the efficiency of energy usage in distribution networks [9]. As a result, these entities are enthusiastic to use innovative alternatives in the DEP problem, to decrease the cost of supplying loads at an acceptable level of reliability.

1.2. Literature review and contributions

Initially, a number of authors solved a simplified form of the DEP problem, using a traditional least-cost approach with economic and technical constraints [10–13]. Their works considered single-objective optimization models, ignored value-based reliability assessment, and neglected the DNO's points of view. Subsequently, the DEP problem was developed to deal with operation of new technologies and options in the distribution networks. Distributed Generation (DG) sources are one of the most effective options in the DEP problem. This is because of the fact that (i) DGs are nearer the load

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points; and therefore, can considerably reduce costs of transmission and distribution, (ii) DGs require less time for installation and (iii) associated investment risks are low [14,15]. A number of authors used DG sources as an operation alternative in power flow [16,17], while others incorporated DG sources in problems of operation and planning; and therefore, determined optimal siting and sizing of DGs [18,19]. These approaches considered insufficient objective functions, neglected the DNO's points of view, used inappropriate optimization techniques with low convergence speed and utilized deterministic approaches for evaluating reliability. On the other hand, the approaches used to evaluate system reliability in the DEP problem can be divided into three categories: customer-oriented, analytical and energy-based approaches. Among the customer-oriented approaches the most widely used include System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), and Average Energy Not Supplied (AENS) [20–22]. The SAIFI is a measure of how many sustained interruptions an average customer will experience over the course of a year [20]. The SAIDI is a measure of how many interruption hours an average customer will experience over the course of a year [20]. Also, the CAIDI is a measure of how long an average interruption lasts, and is used as a measure of utility response time to system contingencies [21]. These deterministic indices are obtained based on average values, which provided little information of risks and could not depict an exact view of the intensity of an outage. Among the approaches of analytical, the Monte-Carlo simulation [23], life curves-based methods [24], Markov [25], Semi-Markov [26,27] and Weibull–Markov approaches [28] were used to predict and asses the composite power system reliability. The idea of Monte-Carlo simulation is the generation of random events in a computer model, and this generation is repeated many times and count the occurrence number of a specific condition [23]. The Monte-Carlo simulation allows us to consider various aspects of system characteristics which cannot be captured by mathematical methods such as, redundancies, repair and maintenance for components. The Markov-based models are a specific stochastic process that is independent of all the past states except the immediately preceding one. The probability of failure or repair for a fixed interval of time is constant for a Markov process. Power system components can be represented by discrete system states with constant transition rates between these states [27,29]. The transition rates between the states are reliability indices. Other analytical approaches that have been used for assessing durability and reliability of a radial distribution network include genetic algorithm [30] and particle swarm optimization and shuffled frog leaping [16], ant colony [31], simulated annealing [32], and tabu search [33]. These studies into the reliability-based DEP problem ignored probabilistic reliability indices and presented inappropriate approaches for implementing radial structure with high computational burden. Also, little effort has been directed toward solving the DEP problem by the use of energy-based approaches with respect to customer interruption cost (CIC), which modeled as a single-objective model [34,35].

In this paper, a new multistage framework is presented for reliability-based DEP problem, where expansion options are combinations of feeders, substations, and DGs, as shown in Fig. 1. This decision framework is based on multiple criteria whose fundamental elements are value of reliability and minimization of the total costs over the planning stages. In this proposed model, reinforcement and/or installation costs of the substations, reinforcement and/or installation costs of the feeders, and installation costs of the DGs were considered as the Total Cost of Expansion Index (TCEI) for the cost analysis of each plan [19,35]. Operation costs of the DGs and the cost of power purchased from the electricity market were taken into account as the Total Cost of Operation Index (TCOI) [18]. The maintenance costs for each initial or candidate feeder and substation were considered as the Total Cost of Maintenance Index (TCMI) [35]. A

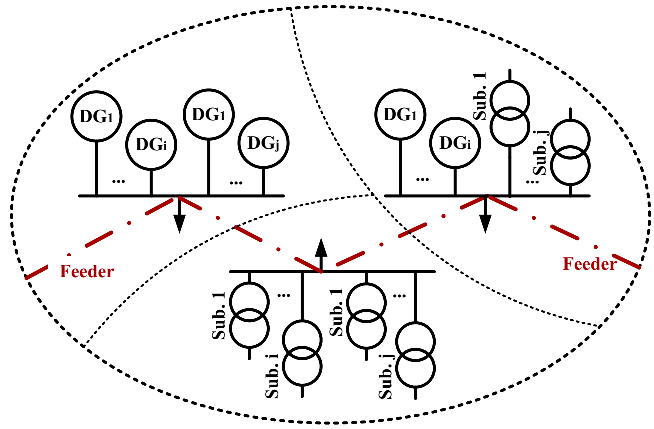

Fig. 1. Expansion plan options for the proposed multistage DEP.

probabilistic criterion, EEIC, was considered for assessing the value of reliability [36,37]. This model simultaneously optimizes four objectives, while taking into account operational restrictions, Kirchhoff's laws, radial structure limitation, voltage limits, and capital expenditure budget restrictions as constraints of problem. Therefore, effective factors of the DEP were integrated in the presence of the DGs and formulated as a multi-objective model. The newly proposed model is a non-convex optimization problem having a non-linear, mixed-integer nature. Therefore, a hybrid Self-adaptive Global-based Harmony Search Algorithm (SGHSA) [38] and Optimal Power Flow (OPF) were used and followed by a Fuzzy Satisfying Method (FSM) [39] in order to calculate the final optimal solution. Due to the subjective, imprecise nature of the decision-maker's judgment, the FSM was implemented here to select the preferred solution from among solutions obtained in the optimization. The discrete decision-making variables of the expansion plan were optimized by the SGHSA, while OPF optimized the continuous ones. The planning methodology was illustrated on the 27-node, 13.8-kV test system [35] to show the feasibility and capability of the proposed algorithm. Attributes of previous models reported in the literature and the model proposed in this study are summarized in Table 1. Given the papers investigated in the literature and compared in Table 1, the main contributions of this study are fourfold:

(1) To incorporate effective factors of the DEP problem in the presence of the DGs as a multi-objective model, which results in a more optimal solution.
(2) To consider a new energy-based approach for evaluating value of reliability in the DEP problem by using a multi-objective model and increase the reliability of the network.
(3) To increase the flexibility of the approach by installation of the DGs as an option for the DEP along with reinforcement and/or installation of the feeders and the substations.
(4) To use a new optimization algorithm to overcome the difficulties in solving the non-convex, mixed-integer non-linear nature of the DEP problem and determine the optimal final solution.

1.3. Paper organization

The rest of this paper is organized into six sections. After an overall classification of the mathematical symbols in Section 2, the mathematical model of the proposed DEP is described in Section 3. The algorithm of the proposed DEP is presented in Section 4. Simulation results and case studies are demonstrated and discussed in Section 5. Finally, conclusions and further research are given in Section 6.

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