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Multistage distribution system expansion planning considering distributed generation using hybrid evolutionary algorithms

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HIGHLIGHTS

- ▶ Presenting a multi-objective framework for distribution expansion planning problem.
- ▶ Considering investment cost, operation cost, and reliability as the objectives.
- ▶ Evaluation of energy-not-supplied using graph theory for assessment of reliability.
- ▶ Finding the Pareto solutions using a hybrid PSO and shuffled frog leaping algorithm.

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ABSTRACT

The main goal of this paper is to present a Multistage Distribution network Expansion Planning (MDEP) problem in the presence of Distributed Generations (DGs) in a multi-objective optimization framework. The proposed model simultaneously optimizes two objectives: minimization of investment and operation costs and maximization of reliability index. The proposed optimization model is solved subject to AC power flow constraints to obtain the optimal configuration of feeders (adding and removing lines) including the optimal size of branch conductor, replacement of conductor for reserve feeders, and generated power of DGs. To include reliability concerns in the proposed MDEP problem, an analytical approach on the basis of graph theory is implemented to evaluate the Energy-Not-Supplied (ENS) index as an extra objective function. Also, in this paper, in order to identify Pareto optimal solutions of the multi-objective MDEP problem, a hybrid Particle Swarm Optimization (PSO) and Shuffled Frog Leaping (SFL) algorithm is implemented. A synthetic distribution test system is considered for the MDEP problem in a 4-year planning horizon. The results of the hybrid PSO and SFL algorithm are compared with those of the classical PSO and SFL methods.

1. Introduction

Distribution networks as a link between the distribution substation network and nodal loads have an important role in power systems' operation. Rapid increase in electrical demand of power networks requires proper expansion planning of both transmission and distribution systems. Expansion planning of distribution networks problem consists of determining the capacity, installation and/or reinforcement of distribution substation units, installing DG units, and addition or replacement of distribution feeders to serve future increasing load demand. Distribution Expansion Planning (DEP) answers the problem of, where when and what type of new feeders and distribution substation lines or DG units should be built with minimum costs in a particular planning period to meet technical requirements and constraints of the system. Also, DEP is a highly complicated optimization problem which involves a set of complex mathematical formulations with high computational burden. This optimization problem has a large number of local optima and when the system size becomes larger, the complexity degree of the problem increases drastically.

To cope with DEP problem, two possible approaches can be adopted: (i) Stage-by-stage planning; in this method the stages would be planned one after the other. In this approach, investment and operation (I&O) cost of each stages is separately optimum, but the total cost of all planning horizon is not optimal [1–3]. (ii) Multi stage planning, in this method planning would be considered by taking all stages together, simultaneously. Due to the interdependency between stages, in this approach I&O cost of each stage may not be optimum, but the total cost of whole planning horizon will be optimal [4–9].

A variety of optimization methods are proposed to solve DEP problem including mathematical programming methods and heuristic evolutionary algorithms. The mathematical programming

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Nomenclature

C_{inv}	investment cost (\$/MVA)
C_{oper}	operation cost (\$/MVA)
N_S	number of stages
N_{Brch}^t	number of all branches in existing and candidate networks in stage t
N_F^t	number of fixed branches in existing and candidate networks in stage t
N_R^t	number of replacement branches in existing and candidate networks in stage t
N_A^t	number of addition branches in existing and candidate networks in stage t
N_{Sub}^t	number of installed distribution substation in stage t
N_{DG}^t	number of installed distributed generation in stage t
$c_{nb_{inv}}^t$	investment cost of nbth branch in tth stage (\$/km)
$c_{ns_{inv}}^t$	investment cost of nsth installed distribution substation at tth stage (\$/MVA)
$c_{nd_{inv}}^t$	investment cost of ndth installed distributed generation in tth stage (\$/MVA)
x_{nb}^t	nbth branch of network in tth stage
x_{fix}^t	fixed branches
x_{rep}^t	replacement branches
x_{add}^t	new branches for addition in the network
x_{ns}^t	nsth exist and candidate distribution substations in tth stage
x_{nd}^t	ndth exist and candidate distributed generations in tth stage
α_t	capital recovery factor
N_{buss}	buses of the exist and candidate networks
ENS_i	energy-not-supplied by the ith bus (MVAh/year)
ENS	total energy-not-supplied by the network (MVA h/year)
V	the set of buses in the network
P_i	active power of the ith bus (MW)
$S_{i\_\max}^{SS}$	maximum output power of the distribution substation transformer (MVA)
$U_{j,i}$	the related service unavailability (h/year)
$U'_{j,i}$	service associated unavailability (h/year)
$\beta_{j,i}$	branches failure rate (fail/year)
$t_{j,i}$	average reparation time (h)
$t'_{j,i}$	average restoration time (h)
$\psi 1$	set of feeders in network at each stage.
$S_{i\_\max}^{fd}$	maximum transmitted power of ith distribution feeder (MVA)
$S_{i\_\min}^{DG}$	minimum power of the ith DGs (MVA)
$S_{i\_\max}^{DG}$	maximum power of the ith DG (MVA)
$v_{\max}$	maximum value of voltage magnitude (kV)
$v_{\min}$	minimum value of voltage magnitude (kV)
δ_i	angle of voltage at the ith bus
$Y_{ij}\angle\theta_{ij}$	line admittance (Ω)
$F_i^{\min}$	lower limits of ith objective function
n	number of parameters (control variables)
N_{rep}	number of individuals in the repository
N_F	number of objective functions

consists of linear programming [10], non-linear programming [11,12], mixed integer programming [13,14], and dynamic programming [15,1]. The heuristic evolutionary algorithms can directly solve the problem with both linear/non-linear objective functions and constraints. In this method, there is no warranty to find the global optimum solution but the solution is close enough and the solving procedure is easy to be implemented. Thus, in this paper, a heuristic method has been adopted. Genetic algorithm [4], simulated annealing [16], tabu search [17], ant colony [18], and modified honey bee mating [19] are some well-known evolutionary algorithms which have been implemented in the area of DEP problem solving.

In addition to the cost, reliability is one of the important factors in the power system planning for future system capacity expansion. Accordingly, considering Energy-Not-Supplied (ENS) of power systems as an objective is very important to have proper level of system reliability which increases satisfactions of consumers. There are some researches in the area dealing with the evaluation of ENS and its respective cost. For instance, in [20] the ENS has been minimized in distribution systems using feeder reconfiguration. Also, reliability improvement and loss reduction by optimal DG allocation in the distribution networks has been addressed in [21]. Reliability-oriented distribution network reconfiguration considering demand uncertainty has been studied in [22]. Besides, in [23], a new framework for optimal DG placement in distribution systems has been proposed while power losses, power quality and reliability enhancement are considered as main objectives of the problem. Arya et al. [24] proposed a technique to determine optimal values of repair times and failure rates for reliability enhancement of radial distribution system. Finally, the ENS cost has been evaluated and minimized via optimal sizing of small wind/battery systems in [25].

To the best of our knowledge, the contributions of the paper with respect to previous works can be summarized as follows:

– System reliability is taken into account in the MDSEP procedure as the extra objective function in the non-linear constrained multi-objective optimization problem. In the proposed scheme, Investment and Operating (I&O) cost and reliability index, i.e., ENS, are treated as competing objective functions. It is noted that in the previous research works in the area, reliability aspects are not considered as constraint or objective function [26,7]. Also, in [27,28], a simple weighting method has been presented to solve the multi-objective problem while in this paper the more efficient Pareto method is proposed to solve the problem. Moreover, a fuzzy decision making tool is also incorporated in the proposed solution method for the multi-objective problem. Considering the imprecise nature of the decision-makers' judgment, it is reasonable to assume that the decision-maker may have fuzzy or imprecise goals for each objective function. So, the proposed fuzzy decision making tool offers a better judgment among the Pareto optimal solutions to select the best compromise one. We have never seen such a MMP (Multiobjective Mathematical Programming) modeling for the multi-objective problem of MDSEP.
– A hybrid evolutionary algorithm based on Particle Swarm Optimization (PSO) and Shuffled Frog Leaping (SFL) has been proposed to cope with the optimization problem of the MDSEP problem.
– In addition, a simple analytical tool based on the graph theory is proposed to evaluate ENS in this paper that can quickly and efficiently evaluate the system reliability for the DEP problem.

The rest of this paper is organized as follows: Section 2 presents the mathematical formulations of the problem with details of objective functions and the constraints of the problem including the load flow constraints. The multi-objective solution approach,