Chance constrained simultaneous optimization of substations, feeders, renewable and non-renewable distributed generations in distribution network

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The penetration of distributed generators (DGs) is continually increasing in the power sector due to its ability in enhancing technical specifications as well as providing a promising future for power generation in electric networks. The aforementioned objectives will be realized if DG units are allocated optimally and coordinate with distribution network expansion planning. On the other hand, given the stochastic nature of renewable generation and severe fluctuations of load consumption and electricity price, the DGs planning problem should be accomplished under uncertainties. To address these issues, this paper proposes a novel joint chance constrained programming (JCCP) method to fulfill an acceptable level of constraint feasibility for optimal simultaneous expansion planning of HV/MV substations and multiple-DG units along with robust MV feeder routing problem. Our design objective is to determine the optimal site and size of sub-transmission substations and various DG units associated with optimally construction of network by implementing the feeder routing problem with aim to minimize the investment costs, energy not supplied (ENS) cost and energy purchasing cost from upstream network. The diverse objectives are mathematically formulated as an MINLP model and converted into a single-objective function through weighted sum method and subsequently has been minimized by adaptive genetic algorithm. Furthermore, the Taguchi method is utilized in order to furnish an efficient algorithm that can find a satisfactory solution. Finally, the effectiveness of the proposed method is investigated by applying it on the 54-bus distribution network and the obtained results are duly drawn and discussed.

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1. Introduction

By annual increasing of electricity demand in power systems, distribution network should be properly upgraded in order to meet the load growth as well as providing the better service for customers. Distribution network expansion planning (DNEP) is one of the most important solution to upgrade the distribution network which aims to bring these targets who involves in installing new substations or increasing the capacity of existing ones, feeder reinforcement and other cases. In the deregulated environment and by privatization of utilities, these goals should be carried out in such a way that the asset management programs be satisfied as much as possible. Low cost investment subject to technical and operational constraints in the system and also risk management is the main goal of asset management policies. On the other hand, the role of distributed generation (DG) units has become much more important with the deregulation of power industry [1]. These units have become an interesting option in DNEP problem to meet the technical requirements of system and could considerably improve the environmental and technical as well as economic issues of system.

Generally, the DNEP can be categorized into two main phases [2] namely: (i) substation planning and (ii) feeder routing problem. Several references have studied these two phases from various perspectives. As one of the first studies, Crawford in Ref. [3] introduced a mathematical technique to find the optimal size and location of HV/MV substations as well as their service area. In Ref. [4], reference network models (RMs) are implemented for planning of large scale MV/LV substations. Uncertainty in load demand is taken into account in Ref. [5] in which fuzzy mathematics method has been employed to solve the substation placement problem. A new model incorporating a non-discrete function is introduced in Ref. [6] to model the total planning cost of distribution substations and defining its service areas.

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Nomenclature

- $\Omega_s$: Set of candidate and existing substations
- $\Omega_l$: Set of load points
- $\Omega_f$: Set of candidate feeders
- $\Omega_{DG}$: Set of DG units
- $\Omega_{DGt}$: Set of DG types
- $N_S$: Set of generated scenarios
- $\kappa$: Distance correction factor
- $\psi_{\text{min}} / \psi_{\text{max}}$: Maximum/minimum limits of voltage in load point $l$
- $P_{WT,\text{rated}}$: Rated power of WT (kW)
- $P_{PV,\text{rated}}$: Rated power of PV (kW)
- $S_{i}$: Selected capacity of substation $i$ (MVA)
- $S_{\text{exist}}$: Existing capacity of substation $i$ (MVA)
- $C_{\text{cost}}$: Capital cost of substation ($/MVA$
- $L_C$: Cost of loss ($/$MVA
- $\gamma$: Loss factor
- $S_{i,t}$: Loading of substation $i$ at year $t$ (MVA)
- $P_{\text{net},i,t}$: Net active power of bus $i$ at year $t$ (kW)
- $Q_{\text{net},i,t}$: Net reactive power of bus $i$ at year $t$ (kVAR)
- $T_H$: Planning horizon time
- $P_{\text{iron},i}$: Iron loss of substation $i$ (kW)
- $P_{\text{inter}},i$: Interruption cost ($/kWh$
- $P_{\text{cop}},i$: Copper loss of substation $i$ (kW)
- $C_{D}$: Capital cost of feeder ($$
- d_{i}$: Distance of feeder $i$ (km)
- $r_{i}$: Resistance of feeder $i$ ($$/M$
- $x_{i}$: Reactance of feeder $i$ ($$$/M$
- $P_{\text{PF}}$: Power Factor
- $I_{f,i,t}$: Current of feeder $f$ at year $t$
- $P_{\text{DC},i,j}$: Power of $i$th DG with type $j$
- $C_{\text{cost},j}$: Capital cost of type $j$ DG ($$
- M_{\text{cost},j}$: Maintenance cost type $j$ DG ($$
- F_{\text{P},t}$: Fuel price at year $t$ ($$/kWh$
- $P_{\text{load},i,t}$: Load in bus $i$ and at year $t$ (kW)
- $E_{\text{P},t}$: Energy price at year $t$ ($$/kWh$
- $\lambda_{i}$: Failure rate of feeder $i$ (fr/year)
- $r_{i,i,t}$: Outage duration of bus $i$ affected by failure of feeder $i$, at year $t$ (h)
- $T_H$: Total number of hours in a year (h)
- $K$: Permissible loading level of substation
- $U$: Nominal voltage of network (kV)
- $P_{\text{WT}}$: Present worth at year $t$
- $\text{infr}$: Inflation rate
- $\text{intr}$: Interest rate

The DNPE problem is complex and, by its nature, mixed integer, nonlinear and nonconvex as well as non-smooth. There is no consensus on which optimization method is more capable than others in solving the problem. In Ref. [7] by using distribution functions for load changes and daily hour cycle, the locations of substations are founded by probabilistic methodologies. For the first time in Ref. [8], the free capacity of medium voltage feeders is considered in the substation expansion planning problem and the related cost function. An approximated technique to solve the DNPE problem for large scale system has been proposed in Ref. [9] corresponding to branch exchange of the radial network. Optimal sizing, siting and timing of substations and feeders in DNPE are obtained by pseudo dynamic planning model in Ref. [10]. Feeder routing problem is discussed in order to expand of distribution system in Ref. [11]. Ref. [12] investigated large scale distribution planning problem by applying clustering technique to allocate the HV/MV substations and also dividing the network to mini-zones in order to improve the load grouping. A novel approach is addressed in Ref. [13] which considered the urbanity uncertainties and its minus effect on the distribution expansion and specifically the feeder routing problem. An optimal multistage planning model is applied to expand the distribution network in Refs. [14] and [15] considering the dynamic behavior of system parameters and geographical constraints. Also, the minimum spanning tree (MST) approach is considered in Ref. [14] to have an optimal radial structure in feeder routing issue. In Ref. [16], a risk based method relies on conditional value at risk (CVaR) technique and is utilized for optimal planning of distribution network in which different risk strategies are implemented and tested to show the impacts of risk analysis on the DNPE problem.

The DNPE problem can be solved through various ways such as single-objective or multi-objective models, bi-level framework, and also multistage programming. Furthermore, the DNPE models presented in the literature are either static or dynamic. In the static planning models, all investment decisions are made at the beginning of the planning horizon, while in the dynamic models the investment decisions determine during planning horizon time. A multi-stage DNPE in the presence of distributed generators (DGs) is introduced in Ref. [17] based on pseudo dynamic procedure. In Refs. [18] and [19] new two stage optimization methods are proposed for multiyear expansion planning in distribution system to determine the optimal size and site of DG units as well as HV/MV substations and MV feeders. In Ref. [20], a dynamic multi-objective model is proposed for DG integrated expansion planning of distribution system. Reliability and security of energy is considered in DNPE problem in Ref. [21] where the feeders are integrated with the DG units. By incorporating the renewable resources in DNPE, the islanding capability in the presence of these units and their uncertainties are considered to get more accurate solution [22]. A stochastic multi-objective approach based on Monte Carlo simulation (MCS) is applied to solve the DNPE problem in Ref. [23] to create a tradeoff between the cost and reliability in determination of the size and location of distribution substations and DG units.

However, the DNPE problem is investigated in previous references, but integrated DNPE and various DG units planning problem considering cost-reliability based objective is not reported simultaneously in previous literature. Also, they have not considered various objective such as reliability, economic and technical issues coordinate. Moreover, the uncertainties of the problem must be taken into account and the risk of uncertainty should be analyzed. To fill out these gaps, this paper proposes a novel joint chance constraint programming (JCCP) approach to cope with uncertainty in solving the simultaneous substation and DG placement (SSDGP) problem. The various objectives are considered in the proposed model such as investment costs, reliability cost and energy purchasing cost which have been mathematically formulated as Mixed Integer Non-Linear Programming (MINLP) and converted into a single-objective function through weighted sum method. Finally, the obtained model has been minimized by adaptive genetic algorithm. Thus, by applying the proposed JCCP based model the optimal size and site of HV/MV substations, feeders and DG units are determined whereas the risks associated with uncertainties are managed. JCCP has the capability of deriving the deterministic equivalent of related constraints and handling the risks associated with uncertainties that are inherent with SSDGP. These uncertainties include renewable resources generation, energy price and load growth and will be fully discussed in the next section. The main contributions of this paper can be summarized as follows:

- Adapting an innovative JCCP method to cope with the technical and financial uncertainties.
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