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Dynamic expansion planning of sub-transmission substations and defining the associated service area

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A B S T R A C T

In this paper, a new methodology is presented for dynamic expansion planning of sub-transmission substations (DEPSS). The proposed method deals with the expansion schemes of the facilities which should be installed and/or reinforced in order to make the sub-transmission system capable of supplying the forecasted demand at the lowest cost while all technical constraints are satisfied. DEPSS is inherently a mixed integer nonlinear programming (MINLP) problem due to the prevalent electrical and expansion constraints, cost indices in objective function and decision variables. This nonlinear problem is simplified to a linear problem without any neglecting by the proposed method. The location, capacity and construction time of substations and MV feeders, as well as the optimal service area of substations are determined through a dynamic approach for the planning years. Meanwhile, the optimal operation capacities of substations are determined at each load level in every planning year. The effectiveness of the proposed optimization method is discussed in the first case study which is related to just placement and defining the associated service area. Also, the proposed dynamic method is tested on a realistic case study and compared with the static and multistage approaches.

1. Introduction

Sub-transmission system is a part of power system which is located between transmission and distribution networks and connects energy sources in the extra high voltage transmission network to medium voltage load points [1]. Dynamic expansion planning of sub-transmission systems (DEPSS) determines the expansion scheme of facilities which should be installed and/or reinforced so that the system can supply the forecasted demand at the lowest cost and all the technical constraints in the planning periods are satisfied. This target is achieved by optimizing the allocation of system elements, such as substations and MV feeders, and determining their time of construction.

In many papers, the expansion planning of sub-transmission substation and MV feeders are investigated considering the primary distribution system. In Ref. [2], the concept of loss characteristic matrix is introduced. Then, the minimum spanning tree and genetic algorithms are employed to generate a set of feasible initial population and determine the optimal HV substations allocation with feeders routing, respectively. In Ref. [3], a new procedure for optimal design of distribution networks is presented by separating the problem in several smaller sub-problems. Thus, the proposed methodology may be interpreted as an optimal combination of optimal sub-problems. The service areas are defined using three methods: (1) Expert planner operational experience, (2) Voronoi diagram, and (3) *K*-means clustering. A hierarchical dynamic optimization model is introduced in Ref. [4] for planning and energy scheduling in power distribution systems. In Ref. [5], the suitability and desirability of alternative planning solutions is assessed using multiple criteria decision making (MCDM) techniques for distribution system planning (DSP). Then, by comparing the cost of each solution with a capital budget, the most desirable solution can be determined. In Ref. [6], the operations research methods are utilized for simultaneously optimizing the substation size, as well as the service boundaries to distribution regulation. An integrated method for distribution system planning with respect to the future scenarios is presented in Ref. [7], in which, the proposed method is able to apply and assess the impacts of massive deployment of DG, demand response programs and electric vehicle penetration on distribution costs. The branch-exchange and dynamic programming algorithms are used in Ref. [8] to co-optimize the layout and conductor type in a radial distribution network. In Ref. [9], a planning methodology for low-voltage distribution networks is presented

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Nomenclature

Sets

i index of substation (both existing and candidate)
j index of load point
h index of planning year
t index of load level

Binary variables

β_{ij} binary decision variable that is equal to 1 if the substation i supplies the load point j; otherwise, it is 0

Integer variables

$int_{i,h}^{sub}$ integer decision variable, if the substation i is installed or expanded in the year h, its capacity will be proportional to $int_{i,h}^{sub}$. Otherwise, it is 0
$\hat{S}_{i,h}^{sub}$ installation and expansion capacity of the substation i in the year h (MVA)

Variables

$S_{i,h,t}^{sub}$ operation capacity of the substation i at the load level t in the year h (MVA)
$S_{ij,h,t}^{feeder}$ operation capacity of the new feeder that connects the ith substation to the load point j at the tth load level of the year h (MVA)

Parameters

$Trans^{Cap}$ minimum amount of expansion or installation that can be implemented in substations
$S_{j,h,t}^{dem}$ demand of load point j at the load level t in the year h (MVA)
$S_{j,h,base}^{dem}$ forecasted base demand of the load point j in the year h (MVA)
D_{ij} distance between the substation i and the load point j (km)
PW present worth or economic coefficient in the planning horizon
$\lambda_{i,h,t}^{grid}$ cost of 1 MWh energy purchased from the upper network of substation i at the load level t in the year h (\$/MWh)
C_i^{sub} total expansion and maintenance costs of substation i within the planning periods (\$/15 MVA)
k_f investment cost of MV feeder (\$/km)
$Max_{int}^{sub}(i)$ maximum capacity that can be installed at the location of candidate substation (i)
S_{feeder}^{max} maximum capacity of feeder (MVA)
R electrical resistance of MV feeders (Ω/km)
V_i voltage of the ith candidate substation (kV)
$\Delta V_{\max}$ maximum allowable voltage drop (%)
DLF_t demand level factor at the load level t (per unit)
$GRIDPLF_t$ price level factor of the purchased energy from the grid (per unit)

based on the combined optimization of transformers and associated networks, considering the street layout which connects different consumers. In Ref. [10], a mathematical model is introduced which simulates the growth of power system and determines the least cost expansion plan for a system of distribution substations employing the linear and integer programming approaches. This model optimizes the system's substation capacities subjected to the constraints of cost, load, voltage and reserve requirements. In Ref. [11], the optimal sizing, location and timing of the distribution substations and feeder expansion is computed separately based on the mixed-integer programming (MIP). Moreover, the investment costs, as well as the system energy and demand losses during the planning period, are minimized. In Ref. [12], a basic and extended planning model is presented based on a pseudo dynamic methodology for solving the expansion problem of distribution substations and feeders. In Ref. [13], a non-discrete substation planning model is proposed, in which, the cost function contains an actual representation of both fixed and variable costs of substations. Meanwhile, the substation construction timing is defined utilizing a pseudo-dynamic planning procedure. In Ref. [14], the proposed model applies linear functions to express the total cost function. Moreover, the planning problem is formulated as a mixed integer linear programming (MILP) problem in order to avoid nonlinear programming which may be trapped in the local minimum solutions. In Ref. [15], for optimal location, sizing and determining the service areas of HV/MV substations in a long range planning period using a pseudo dynamic methodology, the costs of equipment, areas, cables in MV side and power loss are considered in the final cost function. In Ref. [16], a new approach to substation expansion planning is proposed using an appropriate objective function with various constraints, and the main problem is optimized based on the genetic algorithm (GA). A probabilistic methodology to calculate the perimeter of the area where the load center has maximum likelihood to be found is presented in Ref. [17], considering the hourly load changes (load cycles) in the planning process. Afterwards, the final decision of locating the substation site should be made within the calculated area, considering the availability of land lots, as well as market prices and several other factors. In Ref. [18], a new method is presented for determination of maximum load using a single contingency emergency policy for planning of substation capacity. This comprises two linear programming (LP) models which determine: (1) maximum substation's load capacity; (2) reallocation of load when a substation's demand cannot be met. In Ref. [19], the optimal planning problem of distribution substations is solved using a new procedure which doesn't require to candidate substation location and automatically selects the optimal sizes and locations of substations in distribution systems.

The classification of some researches about expansion planning of sub-transmission substations is listed in Table 1. This classification shows that the presented methods in Refs. [2–9] and [16–19] are proper for placement of substation (include sitting and sizing). Also, the presented methodology in some of them contains two parts. In the first section the location and size of the substations are determined and then the service area of substations is decided in the second section. It is obvious that this approach cannot lead to global optimal results. Because, construction costs of MV feeder is a part of the objective function in sub-transmission systems.

In Ref. [20], both geographic information system (GIS) and distribution database are employed to determine the optimal substation and feeder planning based on the minimum feeder loss. In Ref. [21], a modified fuzzy membership matrix, as well as a memorable cost index vector, is introduced to find the optimal substation service areas. Besides, a learning automata-based algorithm is proposed for simultaneous determination of optimal service areas and distribution substations capacity. In Ref. [22], the effect of distributed generation on the expansion planning of sub-transmission system is evaluated using a mathematical model. Moreover, optimal location and capacity of distributed generation (DG) units, as well as optimal configuration of sub-transmission lines, is obtained using GA and LP. An integrated approach based on the tribe particle swarm optimization (TPSO) and ordinal optimization (OO) is developed in Ref. [23] to obtain the expansion planning strategy. In Ref. [24], a hybrid multi-objective immune genetic algorithm (IGA)