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An approach for simultaneous distribution, sub-transmission, and transmission networks expansion planning

H. Kiani Rad, Z. Moravej *

Faculty of Electrical & Computer Engineering, Semnan University, Semnan, Iran

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ABSTRACT

Sub-transmission network, as an intermediate grid between the distribution and transmission systems, receives the electric energy from the transmission network at extra high voltage levels, and delivers it to the distribution network at medium or low voltage levels. The adequate design and operation of sub-transmission system will lead to an efficient design of transmission network from the technical and economic viewpoints on one hand and the adequacy of power delivery to the distribution loads on the other hand. Therefore, the design optimality of these three networks is highly dependent on each other. However, as the simultaneous design of distribution, sub-transmission, and transmission systems is highly complicated, very few researches have tried to model and solve such a difficult problem. In this paper, a new approach has been developed for simultaneous distribution, sub-transmission, and transmission networks expansion planning. The proposed approach has been formulated as an optimization problem where an efficient and improved genetic algorithm (GA) is employed to solve such a complex problem. The utilized GA has been equipped with different modifying operators in order to make sure of its appropriate performance in obtaining useful and optimal solutions for the coordinated planning problem. The conducted approach has been implemented on a real network of Zanjan Regional Electrical Company (ZREC), and the results are compared with those of conventional method, i.e. separate expansion planning of these networks. The simulation results demonstrate the effectiveness of the conducted approach.

1. Introduction

Power system expansion planning is one of the important parts of power system studies which determines the way of reinforcing the capacity of power system elements in order to adequately supply the future load demand in an economical manner regarding the network's operational constraints [1]. This capacity reinforcement would be required in generation, transmission, and distribution levels. The distribution and transmission networks are linked to each other through the sub-transmission system. This intermediate system, composed of sub-transmission lines and substations, receives the electric energy from the transmission network at extra high voltage (EHV) levels, and delivers it to the distribution network at medium or low voltage (MV or LV) levels [2]. In this regard, the adequate design and operation of sub-transmission system will lead to efficient design of transmission network on one hand, and the adequacy of power delivery to distribution loads on the other hand [1,2]. Since the distribution, sub-transmission, and transmission networks are interconnected, the design and expansion planning of each of them is not independent from the others; i.e. the expansion planning of each network will affect the operation of the other two networks [3]. In this regard, it is ideal to consider the whole network in the expansion planning process; that is, the distribution, sub-transmission, and transmission networks should be simultaneously regarded in the expansion planning problem in order to gain an appropriate plan for the whole network. On the other side, as implementing the simultaneous expansion planning is very complicated, the researchers and network planners usually divide the simultaneous expansion planning into three separate sub-problems: 1- distribution expansion planning, 2- sub-transmission expansion planning, and 3- transmission expansion planning [1,2]. This separation makes the planning problem easier to solve, but it may lead to inappropriate results for the network plan due to disregarding the structural dependency of these three networks to each other [3]. To visualize this fact, consider a simple structure of the power system illustrated in Fig. 1. It is aimed to design the network through the possible candidates shown in Fig. 1(A). For this aim, as mentioned earlier,

* Corresponding author.
E-mail addresses: kiani@semnan.ac.ir (H. Kiani Rad), zmoravej@semnan.ac.ir (Z. Moravej).

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Nomenclature

nlp	number of load points
nss	number of sub-transmission substations
$ness$	number of existing sub-transmission substations
$ncss$	number of candidate sub-transmission substations
nts	number of transmission substations
$nets$	number of existing transmission substations
$ncts$	number of candidate transmission substations
α_{ij}^{f}	binary variable for replacement of existing feeder ij
α_{ij}^{sl}	binary variable for upgrading the capacity of existing sub-transmission line ij
α_{i}^{ss}	binary variable for upgrading the capacity of existing sub-transmission substation i
α_{i}^{ts}	binary variable for upgrading the capacity of existing transmission substation i
β_{ij}^{f}	binary variable for installation of new feeder ij
β_{ij}^{sl}	binary variable for installation of new sub-transmission line ij
β_{i}^{ss}	binary variable for installation of new sub-transmission substation i
β_{i}^{ts}	binary variable for installation of new transmission substation i
ξ_{ij}^{f}	binary variable for feeder path
ξ_{ij}^{sl}	binary variable for sub-transmission line path
L_{ij}^{f}	length of feeder between buses i and j
L_{ij}^{sl}	length of sub-transmission line between buses i and j
R_{ij}^{f}	resistance of feeder ij
X_{ij}^{f}	reactance of feeder ij
R_{ij}^{sl}	resistance of sub-transmission line ij
I_{ij}^{f}	current of feeder ij
I_{ij}^{sl}	current of sub-transmission line ij
$I_{ij,max}^{f}$	thermal capacity of feeder ij
$I_{ij,max}^{sl}$	thermal capacity of sub-transmission line ij
$\cos\theta_{ij}$	power factor of load at located the end of feeder ij
ΔV^{max}	maximum permitted voltage drop
rf_i	reserve factor of sub-transmission substation i
V	network rated voltage
S_{j}^{lp}	load of jth load point
S_{i}^{ss}	capacity of ith sub-transmission substation
$S_{i}^{ss,max}$	thermal capacity of ith sub-transmission substation
$S_{i}^{ts,max}$	thermal capacity of ith transmission substation

there are two approaches: separate and simultaneous planning. In separate planning, in the first stage, the load points are optimally allocated to sub-transmission substations; and then, in the second stage, the transmission substations are designed to optimally supply the sub-transmission substations which are obtained from the first stage. But, in the simultaneous planning, the whole network is designed coordinately without any separation. These two approaches have been illustrated in parts (B) and (C) of Fig. 1. In this figure, the circles represent the MV/LV load points; the triangulars are the HV/MV sub-transmission substations; and the squares show the EHV transmission substations. In addition, the MV feeders and HV lines are shown respectively by black and pink lines. The dashed and bold substations/feeders/lines represent the candidate and installed ones, respectively. In the separate expansion planning (shown in Fig. 1(B)), in the stage that the sub-transmission substations and MV feeders are designed, the planning algorithm will try to locate the sub-transmission substations possibly near the MV/LV load points in order to shorten the length of MV feeders; however, as the configuration of the upward grid (including sub-transmission lines and transmission network) are not regarded in this stage, the constructed HV/MV substations may be located far from the transmission system; this leads to longer HV lines that may bring about higher power losses and voltage drop. Contrariwise, in the simultaneous planning (shown in Fig. 1(C)), the algorithm regards both the MV/LV load points and the upward grid to locate the sub-transmission substations near to the load points and no farther from the upward grid. This instance along with lots of other issues related to considering the interactions and dependencies among the whole network equipment demonstrate the advantages of simultaneous planning versus separate planning.

Extensive works have been proposed in the literature for implementation of separated expansion planning. Among them, many researchers have addressed the planning problem of HV/MV sub-transmission substations [4–12]. This process, known also as MV distribution planning, aims at determining the service area of HV/MV substations (the way that the MV/LV load points are fed from these substations) as well as finding the optimal location and capacity of HV/MV sub-transmission substations. In [5], a constructive heuristic algorithm (CHA) has been used to solve the power distribution system expansion planning problem. By employing a local improvement phase and a branching technique in CHA, the algorithm tries to find the optimal location and capacity of MV feeders as well as HV/MV substations. The objective function to be minimized includes the system operational costs and the cost of constructing feeders and substations by taking into account the power flow, voltage drop, and radial configuration constraints.

In [6], a model is proposed for solving the multistage planning problem of a distribution system. The objective function is the net present value of the investment cost to add, reinforce, or replace the feeders and substations, the losses cost, and operation & maintenance cost. The model considers three levels for the loads. The nonlinear objective function is approximated by a piecewise linear function, resulting in a mixed integer linear model that is solved using the standard mathematical programming. Ref. [8] has formulated the planning problem of primary distribution networks as a multi-objective mixed-integer non-linear programming (MINLP) model in order to minimize the expansion and operational costs of the network as well as the system's reliability cost. The cost components of this model consist of the expansion and operation costs of distribution network's equipment, including the transformers, lines, and sectionalizing switches, as well as the system's reliability costs in the contingency events; a multi-objective reactive tabu search (MORTS) algorithm is proposed to optimize the problem. In [9], the authors proposed a multistage framework for the expansion planning of sub-transmission substations and MV feeders in the presence of distributed generation (DG). The presented framework takes into account the investment, operation, maintenance, and customers' interruption costs by considering the load flow, voltage drop, network radiality, and budget restrictions; a hybrid self-adaptive global-based harmony search algorithm (HSA) and optimal power flow (OPF) are employed to search for the optimal solution. Refs. [10–12] has implemented the same research using genetic algorithm (GA), modified particle swarm optimization (MPSO), and frog leaping algorithm (FLA). The obtained results show the positive effects of DGs on the designed