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Coordinated transmission substations and sub-transmission networks expansion planning incorporating distributed generation

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ABSTRACT

Transmission and distribution systems are linked to each other through the sub-transmission network, where it receives the electric energy from the transmission network at extra high-voltage levels, and delivers it to the distribution network at low-voltage level. Hence, if the sub-transmission network is designed in an optimal manner, it will supply the loads of distribution system adequately on one hand, and this leads to an efficient design of transmission network on the other hand. As the design optimality of transmission, sub-transmission, and distribution systems are dependent on each other, the best result for the network expansion is achieved when these three networks are considered coordinately. Since implementing the coordinated design of transmission, sub-transmission, and distribution systems is very complicated, traditionally, they are designed separately. In this paper, a new formulation has been developed for the coordinated expansion planning of transmission substations, sub-transmission network, and distribution system. In addition, to obtain more efficient results for the network expansion, distributed generation (DG) units are considered in the problem. The proposed approach is implemented on a real network of Zanjan Regional Electrical Company, and the results are discussed. The obtained results demonstrate the effectiveness of the conducted planning method.

1. Introduction

Power system expansion planning, as a major part of the power system studies, determines the characteristics of network equipment to be installed or upgraded in order to reliably supply the loads in an economical manner. The expansion planning study is performed in three levels of generation, transmission, and distribution systems. Sub-transmission system is an intermediate system between the transmission and distribution networks that receives the electric energy from the transmission system at extra high-voltage (EHV) levels, and delivers it to the distribution network at low-voltage (LV) levels [1]. In this regard, the adequate design and operation of sub-transmission system will lead to an efficient design of transmission network on one hand and the adequacy of power delivery to the distribution loads on the other hand [1,2]. Different models have been presented in the literature for the optimal design of HV/MV sub-transmission substations [3–7]. In Ref. [4], 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 seeks for the optimal location and capacity of MV feeders and HV/MV substations. The objective function to be minimized includes the system operating costs and cost of constructing feeders and substations by taking into account the power flow, voltage drop, and radial configuration as the problem constraints. Authors in Ref. [5] proposed a model 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, and also, the losses cost, and operation and maintenance costs. The nonlinear objective function of the problem is approximated by a piecewise linear function, resulting in a mixed integer linear model that is solved using standard mathematical programming. Moreover, the reliability indices and the related costs are computed for each solution based on the regulation model of Brazil. An approach is proposed in Ref. [6] for the planning of low-voltage distribution systems where the location, number, and capacity of distribution transformers are optimally determined for the sake of improving the system reliability and minimizing the power and energy losses under energy demand growth. The considered objective function is

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Nomenclature

Constants

nets	Number of existing transmission substations
ncts	Number of candidate transmission substations
nts	Total number of transmission substations
ness	Number of existing sub-transmission substations
ncss	Number of candidate sub-transmission substations
nss	Total number of sub-transmission substations
nlp	Number of load points
nsl	Number of sub-transmission lines
$n_{i,\max}^{DG}$	Maximum installable DG units on bus
$n_{i,\max}^{tr}$	Maximum installable transformers on bus i
L_{ij}^{sl}	Length of sub-transmission line in ij path (km)
L_{ij}^{f}	Length of MV feeder in ij path (km)
R_{ij}^{f}	Resistance of feeder in ij path (ohms)
X_{ij}^{f}	Reactance of feeder in ij path (ohms)
R_{ij}^{sl}	Resistance of sub-transmission line in ij path (ohms)
RC	Reliability cost ($/kW)
LC	Loss cost ($/kW)
λ_i^{tr}	Failure rate of transformer located on sub-transmission substation i (fail/year)
r_i^{tr}	Repair time of transformer located on sub-transmission substation i (hr)
λ_i^{sl}	Failure rate of ith sub-transmission line (fail/(km.year))
r_i^{sl}	Repair time of ith sub-transmission line (hr)
$\Delta V^{\max}$	Maximum permitted voltage drop (p.u.)

Variables

n_i^{tr}	Number of transformers installed on ith sub-transmission substation
n_i^{DG}	Number of installed DG units on ith sub-transmission substation
LNS_i^{tr}	Load not supplied due to the outage of transformer located on sub-transmission substation i (kW)
LNS_i^{sl}	Load not supplied due to the outage of ith sub-transmission line (kW)
I_{ij}^{f}	Current flowing through the feeder in ij path (A)
I_{ij}^{sl}	Current flowing through the sub-transmission line in ij path (A)
$I_{ij,\max}^{f}$	Thermal capacity of feeder ij (A)
$I_{ij,\max}^{sl}$	Thermal capacity of sub-transmission line ij (A)
$P_{loss,i}^{iron}$	No-load power loss of ith sub-transmission substation (kW)
$P_{loss,i}^{cu}$	Load power loss of ith sub-transmission substation (kW)
S_i^r	Rated capacity of the transformer located on ith sub-transmission substation (kVA)
S_i	The power flowing through the transformer located on ith sub-transmission substation (kVA)
$S_i^{ts,max}$	Thermal capacity of ith transmission substation (kVA)
θ_{ij}	Power factor of load flowing through the feeder ij

Functions

$EC_{ts,i}(S_{ts,i}^{old}, S_{ts,i}^{new})$	Cost of expanding the capacity of ith existing transmission substation from $S_{ts,i}^{old}$ to $S_{ts,i}^{new}$ ($)
$IC_{ts,i}(S_{ts,i}^{new})$	Cost of installing new transmission substation i with the capacity of $S_{ts,i}^{new}$ ($)
$EC_{ss,i}(S_{ss,i}^{old}, S_{ss,i}^{new})$	Cost of expanding the capacity of ith existing sub-transmission substation from $S_{ss,i}^{old}$ to$S_{ss,i}^{new}$ ($)
$IC_{ss,i}(S_{ss,i}^{new})$	Cost of installing new sub-transmission substation i with the capacity of $S_{ss,i}^{new}$($)
$EC_{sl,ij}(S_{sl,ij}^{old}, S_{sl,ij}^{new})$	Cost of expanding the capacity of existing sub-transmission line in ij path from $S_{sl,i}^{old}$ to $S_{sl,i}^{new}$($)
$IC_{sl,ij}(S_{sl,ij}^{new})$	Cost of installing new sub-transmission line ij with the capacity of $S_{sl,i}^{new}$($)
$FUC_{ij}(S_{f,ij}^{old}, S_{f,ij}^{new})$	Cost of upgrading the capacity of MV feeder from $S_{f,ij}^{old}$ to$S_{f,ij}^{new}$($)
$FIC_{ij}(S_{f,ij}^{new})$	Installation cost of new MV feeder in ij path with the capacity of $S_{f,ij}^{new}$($)
$IC_{dg,i}(S_{dg,i})$	Installation cost of DG unit with the capacity of $S_{dg,i}$ on ith sub-transmission substation ($)
$EC_{ts,i}(S_{ts,i}^{old}, S_{ts,i}^{new})$	Cost of expanding the capacity of ith existing transmission substation from $S_{ts,i}^{old}$to $S_{ts,i}^{new}$($)
$IC_{ts,i}(S_{ts,i}^{new})$	Cost of installing new transmission substation i with the capacity of $S_{ts,i}^{new}$($)
$EC_{ss,i}(S_{ss,i}^{old}, S_{ss,i}^{new})$	Cost of expanding the capacity of ith existing sub-transmission substation from $S_{ss,i}^{old}$to$S_{ss,i}^{new}$ ($)
$IC_{ss,i}(S_{ss,i}^{new})$	Cost of installing new sub-transmission substation i with the capacity of $S_{ss,i}^{new}$($)

composed of investment, maintenance, losses, and reliability cost. It was shown that the appropriate placement of distribution substations leads to considerable reduction of interruption cost. Ref. [7] has proposed a multi-objective mixed-integer non-linear programming (MINLP) model for the planning problem of primary distribution networks in order to minimize the expansion and operation costs of the network as well as the system's reliability cost in contingency events. This study has considered the expansion and operation costs of transformers, lines, and sectionalizing switches, as well as reliability cost as the objective functions to be optimized by a Multi-objective Reactive Tabu Search (MORTS) algorithm. A novel mixed-integer second-order cone programming model is developed in Ref. [8] for the robust multi-stage expansion planning of sub-transmission substations considering the stochastic nature of demand. To take into account the total expected expansion planning cost and the robustness probability, a multi-objective formulation has been proposed, and the classical optimization techniques have been used to optimally solve the problem. The solution gives the construction of new substations, reinforcement of existing substations, and service area of each substation. In addition, the Monte Carlo (MC) simulation is carried out in order to evaluate the extent of the problem constraints satisfaction.

Recently, the integration of distributed generation (DG) resources into distribution networks has affected the planning and operation problems of the power system [9]. These small-scale power generating units bring various benefits to power system such as peak cutting, losses reduction, voltage profile improvement, reliability enhancement, and deferring the capacity reinforcement of network equipment [10–13]. Due to potential