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Integrated distribution network expansion planning incorporating distributed generation considering uncertainties, reliability, and operational conditions

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ABSTRACT

In this paper, an integrated methodology is proposed for distribution network expansion planning which considers most of the planning alternatives. The planning aims to determine the optimal reinforcement of existing medium voltage lines and high voltage/medium voltage substations, or installation of new ones to meet the load growth in the planning horizon subject to the technical and operational constraints. Also, to take the advantages of new technologies, the renewable and non-renewable distributed generations have been included in the problem as another alternative. The uncertainties related to renewable DGs, load demand, and energy price have been considered in the calculation of cost components. The load duration curve has been utilized for loads such that the results be more precise. The possibility of islanding and load transferring through the reserve feeders have been regarded in the problem to improve the reliability of the network. Also, the required condition for successful and safe operation of island considering all of uncertainty states have been checked out to accurately calculate the reliability. The genetic algorithm is employed to solve this integrated problem. Finally, the proposed method is applied to the 54-bus system and also a real large-scale distribution network, and the results are discussed. The results verify the effectiveness of the presented method.

Introduction

Expansion planning of power distribution systems is one of the major activities of distribution utilities to deal with electric power demand growth.

The main objective of the distribution network expansion planning (DNEP) problem is to provide a reliable and cost effective service to consumers while ensuring that voltages and power quality are within standard ranges [1]. Traditionally, this aim is attained through the reinforcement of existing lines and substations, or by installation of new ones regarding to the technical and operational constraints [2–7].

Today, power system economic and operation environment has changed as new capacity options have emerged. Distributed Generation (DG) is one of these new options. The introduction of DG in power system changes the operating features, and has significant technical and economic advantages. Adding DG sources to the planning options is resulting in challenges in the distribution network operation, structure, design and upgrade issues. At present, there are several technologies ranging from traditional to non-traditional used in DG application. The former is non-renewable technologies such as internal combustion engines, combined cycles, gas turbines, and micro-turbines. The latter includes renewable-energy-based technologies such as wind, photovoltaic, biomass, geothermal, etc. Due to the availability of such a flexible option of DG as an energy source at the distribution voltage level, the distribution network is being transformed from a passive network to an active one. In this regard, DG brings about various benefits such as distribution capacity deferral, losses reduction, flattering of peak, improving of voltage profile, and reliability improvement [8–13].

Several researches have been implemented to illuminate the advantages of utilizing DG units in the distribution network. Optimal allocation and sizing of DGs is solved in [14] using an analytical-based method to minimize the line losses. The same problem is solved using an ordinal optimization method in [15]. In addition to line losses, the system's reliability is included in the DG planning problem as a constraint in [16] which tries to improve the system reliability, line losses, and voltage profile using the genetic algorithm (GA). To further improve the system reliability,

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Nomenclature

Constants

n_f	number of network's feeders
n_s	number of HV/MV substations
n_l	number of load buses (MV/LV substations)
n_n	total number of network substations
n_{es}	number of existing HV/MV substations
n_{cs}	number of candidate HV/MV substations for installation
n_{ef}	number of existing feeders
n_{cf}	number of candidate feeders for installation
n_{LL}	number of load levels
ns	number of states
n_y	planning horizon
λ_k	failure rate of feeder *k* (fail/km/year)
PW	present worth factor
Infr	inflation rate (%)
Intr	interest rate (%)
Y_{ij}	magnitude of admittance between buses *i* and *j*
θ_{ij}	angle of admittance between buses *i* and *j*
r_k	repair time of feeder *k* (h)
T_{LL}	duration of load level *LL* (h)
$S^L_{i,LL,s}$	apparent power of load demand in bus *i*, in load level *LL* and state *s*
$S^L_{i,peak}$	apparent power of load demand in bus *i*, in peak condition
$\mathrm{LLF}_{LL,s}$	load level factor for load level *LL* and state *s*
$\mathrm{EP}_{LL,s}$	energy price in load level *LL* and state *s*
EP_{peak}	energy price in peak condition
$\mathrm{PLF}_{LL,s}$	price level factor for load level *LL* and state *s*
$P^L_{i,LL,s}$	active load demand in bus *i*, in load level *LL* and state *s*
$Q^L_{i,LL,S}$	reactive load demand in bus *i*, in load level *LL* and state *s*
$P^L_{i,peak}$	active load demand in bus *i* in peak condition
$S^{DG}_{i,LL,S}$	apparent power of DG installed in bus *i*, in load level *LL* and state *s*
$S^{DG}_{i,max}$	capacity of DG installed in bus *i*
$\mathrm{LC}_{LL,s}$	loss cost in load level *LL* and sate *s* ($/kWh)
RC_{LL}	reliability cost of unsupplied energy in load level *LL* ($/kWh)
$\mathrm{oc}_{LL,s}$	operation cost of DG in load level *LL* and sate *s* ($/kWh)
dc	dissatisfaction cost ($)
Load(*s*)	states of load demand
Price(*s*)	states of energy price
Wind(*s*)	states of wind speed
States^{comb}_s	combination of all states
V^{min}_{safe}	lower limit of buses voltages for safe operating condition
V^{max}_{safe}	upper limit of buses voltages for safe operating condition
V^{min}_{crit}	lower limit of buses voltages for critical operating condition
V^{max}_{crit}	upper limit of buses voltages for critical operating condition

Functions

$\mathrm{sec}_i(S)$	expansion cost of *i*th existing HV/MV substation with the capacity of *S* ($/kVA)
$\mathrm{IC}_i(S)$	installation cost of *i*th new HV/MV substation with the capacity of *S* ($/kVA)
$\mathrm{FC}_{ij}(k)$	cost of installing a feeder with the type of *k* between buses *i*, *j* ($/km)
$\mathrm{MFC}_{ij}(k)$	cost of installing main feeder with the type of *k* between buses *i*, *j* ($/km)
$\mathrm{RFC}_{ij}(k)$	cost of installing reserve feeder with the type of *k* between buses *i*,*j* ($/km)
$\mathrm{DDGIC}_i(S)$	installation cost of dispatchable DG with the capacity of *S* in bus *i* ($/kVA)
$\mathrm{WDGIC}_i(S)$	installation cost of wind DG with the capacity of *S* in bus *i* ($/kVA)

Variables

$\mu^V_{i,LL,S}$	degree of voltage constraint satisfaction for bus *i*, in load level *LL* and state *s*
μ^V_i	degree of voltage constraint satisfaction for bus *i*
μ^V	degree of voltage constraint satisfaction for the whole network
μ^I	degree of current constraint satisfaction for the whole network
μ^S	degree of substation capacity constraint satisfaction for the whole network
$V_{i,LL,s}$	voltage magnitude of bus *i*, in load level *LL* and state *s*
$\delta_{i,LL,s}$	voltage angle of bus *i*, in load level *LL* and state *s*
$P^{WDG/DDG}_{i,LL,s}$	Active power generated by WDG/DDG installed in bus *i*, in load level *LL* and state *s*
$Q^{WDG/DDG}_{i,LL,S}$	reactive power generated by WDG/DDG installed in bus *i*, in load level *LL* and state *s*
PDG_{ijs}	generated power of DG installed in bus *i*, in load level *j* and state *s*
$P^{Trans}_{i,LL,s}$	The power imported from transmission system to distribution network through the *i*th HV/MV substation in load level *j* and state *s*
$\mathrm{LNS}_{k,LL,s}$	the load not supplied in load level *LL* and state *s* due to the outage of feeder *k*

switches, such as reclosers and cross-connections (CCs), are incorporated in the DG-based planning problem. An ant colony system algorithm is employed in [17] for finding the optimal placement of reclosers and DGs. This method minimizes an objective function composed of two reliability indices: system average interruption duration index (SAIDI) and system average interruption frequency index (SAIFI). [18] proposes an integrated methodology for distribution network planning in which the operation of DGs and CCs is optimally planned. Distribution lines and HV/MV transformers are also optimally upgraded in order to improve system reliability and to minimize the line losses under load growth; the objective function is composed of the investment cost, losses cost, and reliability cost; the energy savings resulted from installation of DGs is also included in this function. The constraints are the buses' voltages and lines' currents; the modified discrete particle swarm optimization (PSO) method is employed to optimize the problem is different scenarios.

In the abovementioned works, the considered DG technology is non-renewable and controllable (Dispatchable DG (DDG)). On the other side, the development in technology and the importance of using clean energy resources have made the renewable energies more attractive for distribution network operators, specifically because of their inexhaustible and non-polluting features. Among these renewable energies, wind-based distributed generation (WDG) has emerged very rapidly in recent years. Reduction of capital costs, improvement of reliability, and efficiency have made the wind power able to compete with the conventional power generation [19]. The renewable DG technologies like wind have special