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SoS-based multiobjective distribution system expansion planning

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ABSTRACT

This paper coordinates the reconfiguration of distribution systems with the expansion problem while the potential of demand response (DR) programs and distributed generation (DG) units are modeled in the active distribution expansion planning. The concept of system of systems (SoS) is proposed to model the expansion of DGs that are owned by private investors. SoS is an efficient system consisting of some autonomous and heterogeneous systems with distinct objective functions. According to the concept of SoS, a decision-making paradigm is developed to determine the location, size, and time of DG investment made by a commercial agent, as well as the price of generated power. From the distribution company (DISCO) viewpoint, the proposed model is a multi-objective (MO) optimization problem. The first objective function is the net present value of the total investment and operation costs related to the network. The second objective function is a reliability index, i.e. the expected energy not-supplied (EENS). The uncertainty of load growth in future years is handled by using a scenario-based approach. The introduced problem is solved by using multi-objective particle swarm optimization (MOPSO) algorithm empowered with an innovative three-layer procedure that is provided to better manage the space of the decision variables. The first layer is based on PSO particles while the second and third layers are based on a sensitivity analysis. Finally, a standard 33-bus distribution system is utilized to obtain the simulation results that show the performance and advantages of the proposed method.

1. Introduction

DEP is the determination of time of installation, size and the location of new instruments in order to timely meet the electricity demand in the most economical and reliable way [1]. The planning of distribution systems has been investigated in numerous studies. Multi-objective DEP, the allocation of DGs, the utilization of stochastic models, and the investigation of uncertainties have been proposed in this research area [2–4]. Then, the role of the smart grid and its advantages and challenges have been highly investigated. Alvarez-Herault et al. [5] mentioned the role of smart distribution systems to cope with the network challenges and introduced a new architecture and intelligent systems. In recent years, high penetration of DG units, the participation of responsive customers in the form of active demand, and the automation of distribution systems, have been introduced as the base of the so-called active distribution systems [1]. Su et al. [6] introduced a framework to investigate the planning of DGs. The proposed framework coordinates the DSR and voltage control to compute the maximum permissible DG penetration level. Zou et al. [7] considered the reactive power generation ability of different DGs. The optimization results have determined the optimal size and location of DGs in the distribution network. Kezunovic et al. [8] explained the current trends and future expectations of the system and discussed smart grid barriers mainly in relation to the challenges that utilities should cope with them. By considering these challenges, some novel solutions have been also addressed. According to [8], some of the future expected developments in power systems are: (1) increasing the utilization of variable generation, (2) high participation of customers in all generation and consumption levels, (3) increasing the automation level in both distribution and transmission grids, (4) providing a comprehensive framework and using suitable approaches to cope with the uncertainties, and (5) increasing the standardization level for expediting the progress of new technologies. Pavlos et al. [9] introduced some research areas and suitable contributions in the field of distribution systems including simultaneous DSR, and the allocation

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Nomenclature

Abbreviations

DR	demand response
DG	distributed generation
SoS	system of systems
DISCO	distribution company
MO	multi-objective
SO	single-objective
EENS	expected energy not-supplied
MOPSO	multi-objective particle swarm optimization
O&M	operation and maintenance
DEP	distribution expansion planning
DSR	distribution system reconfiguration
NO	normally open
NC	normally close
NSGA	non-dominated sorting genetic algorithm
NBI	normal boundary intersection
MINLP	mixed integer non-linear programming
MILP	mixed integer linear programming
OPF	optimal power flow
SFLA	shuffled frog leaping algorithm
ABC	artificial bee colony
NLP	non-linear programming

Indicators

y	planning years
n_{cl}	network candidate lines
T	time periods
n_f	network feeders
b^D	candidate buses to install DGs by DISCO
j^D	various types of DGs belonging to the DISCO
b^P	candidate buses to install DGs by the private investor
j^P	various types of DGs belonging to the private investor
m	bus numbers
n^e	expected years from the viewpoint of DG investor to return all the investment, and operation costs

Decision variables

$\chi_{n_{cl}}(y)$	integer variable that is equal to "CT" if feeder "n_{cl}" is reinforced with line type "CT"; otherwise, it is 0
$z_{n_{cl}}(y)$	binary variable that is equal to 1 if feeder "n_{cl}" is reinforced in year "y"; otherwise it is 0
$z_{n_f}(T, y)$	binary variable that is equal to 1 if feeder "n_f" is selected in time period "T" of year "y"; otherwise it is 0
$x^D_{j^D,b^D}(y)$	installed capacity of "$j^{D\,th}$" DG in bus "b^D" in year "y" [kW]
$p^D_{j^D,b^D}(T, y)$	generated power by the "$j^{D\,th}$" DG at bus "b^D" in time period "T" of year "y"[kW]
$C_{b^P}(y)$	guaranteed price for purchasing the generated power of DGs at bus "b^P" in year "y" [$/kWh]
$p^{DR}_m(T, y)$	active power enabled with DR programs at bus "m" and the time interval "T" of year "y" [kW]
$\partial_{n_f}(y)$	integer variable that is equal to "CT" if the type of feeder "n_f" is "CT"; otherwise it is 0
$x^P_{j^P,b^P}(y)$	new installed capacity of "$j^{P\,th}$" DG at bus "b^P" in year "y" [kW]

Variables

$C^{upg}(y)$	network upgrading cost in year "y" [$]
$C^{Loss}(y)$	total cost of energy losses in year "y" [$]
$p^{loss}_{n_f}(T, y)$	active power losses of feeder "n_f" in time period "T" of year "y" [kW]
$C^{tr}(y)$	total cost of imported energy from the transmission grid [$]
$p^{tr}(T, y)$	imported power from the transmission grid in time period "T" of year "y" [kW]
$C^{Dis}_{DG}(y)$	total cost of installing and operating DGs in year "y" [$]
$C^{SoS}_{DG}(y)$	total cost for persuading commercial agent in year "y" [$]
$x^P_{j^P,b^P}(y)$	total installed capacity of "$j^{P\,th}$" DG at bus "b^P" in year "y" [kW]
$C^{DR}_m(T, y)$	cost of DR at bus "m" and time period "T" in year "y" [$/kWh]
$T^{DR}_m(T, y)$	total enabled duration of DR at bus "m" in year "y" [h]
$pf_{n_f}(T, y)$	power flow of feeder "n_f" in the time period "T" of year "y" [kW]
$f^P(y)$	benefit of the private investor in year "y" [$]
$V_m(T, y)$	voltage level of bus "m" in the time period "T" of year "y" [kV]
$I_{n_f}(T, y)$	current of feeder "n_f" in the time period "T" of year "y" [A]
$p^{loss}_{n_f}(T, y)$	active power losses of feeder "n_f" in the time period "T" of year "y" [kW]
$q^{loss}_{n_f}(T, y)$	reactive power losses of feeder "n_f" in the time period "T" of year "y" [kVAr]
$P_{sub}(T, y)$	amount of injected active power from the distribution substation in the time period "T" of year "y" [kW]
$Q_{sub}(T, y)$	amount of injected reactive power from the distribution substation in the time period "T" of year "y" [kVAr]
$q^{DR}_m(T, y)$	reactive power enabled with DR programs at bus "m" and the time interval "T" of year "y" [kVAr]
$D^{DR}_m(y)$	total enabled duration of DR at bus "m" in year "y"
$p^{DG}_m(T, y)$	generated power with DGs at bus "m" in time period "T" of year "y" [kW]

Parameters

$UC(\chi_{n_{cl}}(y))$	installation cost of line "CT" per kilometer [$/km]
$L^{n_{cl}}$	length of line "n_{cl}" [km]
$C^f_{n_{cl}}$	fixed cost of feeder "n_{cl}" [$]
$t(T, y)$	duration of time period "T" in year "y" [h]
$LC(T, y)$	loss cost in time period "T" of year "y" [$/kWh]
$EC(T, y)$	cost of imported energy from the transmission grid in time period "T" of year "y" [$/kWh]
$I^D_{j^D}$	investment cost of "$j^{D\,th}$" DG for DISCO [$/kW]
$C^{O\&M}_{j^D}(T, y)$	O&M cost of "$j^{D\,th}$" DG in time period "T" of year "y" [$/kWh]
i	discount rate
$\lambda(\partial_{n_f}(y))$	failure rate of line "CT" per kilometer and per year [fail/(km year)]
$rp(\partial_{n_f}(y))$	average duration of fault on line "CT" [h/fail]
L^{n_f}	length of line "n_f" [km]
$\alpha_{j^P,b^P}(y)$	correction factor regarding the total power generation hours with the "$j^{P\,th}$" DG at bus "b^P" in year "y"
$C^{O\&M}_{j^P}(y)$	O&M cost of "$j^{P\,th}$" DG in year "y" [S/kWh]
$I^P_{j^P}$	investment cost of "$j^{P\,th}$" DG for the private investor [$/kW]