Applied Energy 219 (2018) 207–225

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Multi-objective active distribution networks expansion planning by scenario-based stochastic programming considering uncertain and random weight of network

Shiwei Xie[a,*], Zhijian Hu[a], Daming Zhou[b], Yan Li[a], Shunfei Kong[a], Weiwei Lin[a], Yunfei Zheng[a]

[a] School of Electrical Engineering, Wuhan University, Wuhan City, Hubei Province, China
[b] FEMTO-ST (UMR CNRS 6174), Energy Department, Univ. Bourgogne Franche-Comte, UTBM, Rue Thierry Mieg, F-90010 Belfort Cedex, France

HIGHLIGHTS

- The uncertain random network theory is originally applied in the ADN planning model.
- A modified scenario-generation procedure is proposed to describe uncertainty sources.
- A numerical second-order cone programming is applied to solve the MINLP model.
- A novel 3-dimensional uncertain space is built to cope with multi-objective problem.
- A sensitivity analysis is performed to find compromise between costs and system performance.

ARTICLE INFO

Keywords:
Multi-objective planning
Active distribution network
Energy management
Uncertain random network
Minimum spanning tree
Stochastic programming

ABSTRACT

This paper presents a novel multi-objective model of active distribution network planning based on stochastic programming and uncertain random network (URN) theory. The planning model is proposed to find the final scheme with optimal alternative, location, size and operational strategy for the candidate distribution lines, transformer substations (TSs), distribution generations (DGs), static var compensators (SVCs) and on-load tap changers (OLTCs). Firstly, a scenario-based approach is developed to analyse the uncertainties in network system, such as the demand and intermittency of renewable sources. Since the impact of multiple uncertain factors on network cannot be ignored, a network frame is then modelled by uncertain and random weights of spanning tree (ST) instead of fixed value. In order to achieve the minimization of total cost, and further the selection of a minimum spanning tree (MST) with the uncertain and random weight, a 3-dimensional uncertain space is constructed based on the combination of the previous two targets. In addition, a second-order cone programming (SOCP) is applied to cope with the multi-objective, mixed-integer nonlinear nature of the proposed planning model. Simulation is performed on a modified Pacific Gas and Electric Company (PG&E) 69-bus distribution system, and the results demonstrate the effectiveness of the proposed model.

1. Introduction

In a centralized power generation system, the electricity is generally supplied by a large-scale generation unit, and transmitted and distributed through network to domestic, commercial and industrial consumers, as shown in Fig. 1(a). In recent years, high penetration of renewable DGs have been considered as one of the key issues for power distribution network system. Among different renewable DGs, wind turbines generations (WTGs) and photovoltaic plants generations (PVGs) have attracted more attention due to their commercial products and supply ability in distribution system [2], as shown in Fig. 1(b). Nevertheless, several challenges have to be addressed before their mass commercialization in distribution network planner (DSP).

Nowadays, the distribution system planning has been successfully implemented by distribution system planners with centralized framework. The primary objective of conventional distribution network planning (DNP) is to identify the optimal expansion of system assets at minimum cost, in order to meet the load growth demand and newly added loads, and at the same time complying with the security requirements and quality standards [3,4]. However, with the widespread growth of distributed generation (DG) penetration, mainly due to renewable energy policy-making [5–7] and its substantial advantages to

* Corresponding author.
E-mail address: Shiwei_Xie@126.com (S. Xie).

https://doi.org/10.1016/j.apenergy.2018.03.023
Received 16 December 2017; Received in revised form 22 February 2018; Accepted 17 March 2018

Nomenclature

Indices and sets

ij	index for lines
i,j	index for buses
b,s	index for time blocks and scenarios
t	index for time stages
p	index for DG types
k	index for available investment alternatives
g	index for spanning trees
B	set of time blocks
$S(b)$	set of scenarios of time block b
T	set of time stages
Ω,Γ	set of uncertain variables and random variables
Ω^{Tree}	set of spanning trees
Π^{Line}	set of candidate replaceable feeders
Γ^{b}	set of all buses
$\Omega^{Line}/\Omega^{Dg}/\Omega^{Tr}$ $\Omega^{SVC}/\Omega^{OLTC}$	set of candidate feeders/DGs/TSs/SVCs/OLTCs
$\Gamma^{Line}/\Gamma^{Dg}/\Gamma^{Tr}$	set of all existing and candidate feeders/DGs/TSs
$K^{Line}/K^{Dg}_{p}/K^{Tr}$ / K^{SVC}/K^{OLTC}	set of available alternatives for feeders/DG(type p)/TSs/SVCs/OLTCs
Λ^{Dg}	set of type for DG. $\Lambda^{Dg}=\{WTG,PV\}$

Parameters and constants

$C^{I,Line}_{k}/C^{I,Dg}_{k,p}/C^{I,Tr}_{k}$ / $C^{I,SVC}_{k}/C^{I,OLTC}$	investment cost of feeders/DG (type p)/TSs/ SVCs/OLTCs with alternative k (\$)
$C^{M,Line}_{k}/C^{M,Dg}_{k,p}/C^{M,Tr}_{k}$ / $C^{M,SVC}_{k}/C^{M,OLTC}$	investment cost of feeders/DG(type p)/TSs/ SVCs/OLTCs with alternative k (\$)
$C^{Tr}_{ope}/C^{WTG}_{ope}/C^{PVG}_{ope}$	operation cost of TSs/WTGs/PVGs (\$/MWh)
$C^{Line}_{loss}/C^{Tr}_{loss}/C^{OLTC}_{loss}$	energy losses cost of network/TSs/OLTCs (\$/MWh)
$\rho(s)$	probabilities of scenario s
ℓ_{ij}	feeder length of line ij
i	annual interest rate
Δt_b	duration of time block b
N_B	total number of time blocks
N_S	number of scenarios per time block
N^{Dg}_{j}/N^{SVC}_{j}	installation number of DGs/SVCs at bus j
$\widetilde{P}^{Dg}_{j,k,p},\widetilde{Q}^{Dg}_{j,k,p}$	rated active and reactive power of DG
z^{OLTC}_{k}	resistance of OLTC/transformer with type k
r_{ij},x_{ij}	resistance and reactance of line ij
P^{L}_{j}	maximum active power of load at bus j
β_{min},β_{max}	minimum and maximum penetration of DG
$\widetilde{U}_{min},\widetilde{U}_{max}$	minimum and maximum permissible voltage
$\lambda^{WTG}/\lambda^{PVG}/\lambda^{L}$	maximum curtailment rate of WTG/PVG/load
$\widetilde{Q}^{SVC}_{max}$	maximum capacity of SVC
$\widetilde{P}^{Tr}_{max},\widetilde{Q}^{Tr}_{max}$	maximum active and reactive power of TS
$\widetilde{I}_{max}$	maximum permissible current of line
$\widetilde{\sigma}_{max}$	maximum permissible tap position value of OLTC
$\widetilde{U}^{OLTC}$	original voltage of OLTC before adjustment
h_k	voltage variation value for changing each tap of OLTC

Variables

$x^{Line}_{ij,k}$	binary investment variable for feeders ij with type k
$x^{Tr}_{j,k}/x^{Dg}_{j,k}/x^{OLTC}_{j}$	binary investment variable for TS/DG(type p)/ OLTC with alternative k at bus j
$x^{SVC}_{j,k}$	integer investment variable for SVC type k at j
$y^{Line}_{ij,k}$	binary utilization variable for feeders ij with type k
$y^{Tr}_{j,k}/y^{Dg}_{j,k}/y^{OLTC}_{j}$	binary utilization variable for TS/DG(type p)/ OLTC with alternative k at bus j
$y^{SVC}_{j,k}$	integer utilization variable for SVC type k at j
$\sigma_{j,s,t}$	integer variable for tap position value of OLTC
$I_{j,s,t}$	current injection at bus j
$U_{j,s,t}$	voltage magnitude at bus j
$\delta(j),\pi(j)$	set of buses whose parent/child is bus j
$P_{j,s,t},Q_{j,s,t}$	active power and reactive power injection at j
$P_{ij,s,t},Q_{ij,s,t}$	active power and reactive power flow via line ij
$P^{WTG,cur}_{j,s,t},Q^{WTG,cur}_{j,s,t}$	curtailment of WTG active/reactive power at j
$P^{PVG,cur}_{j,s,t},Q^{PVG,cur}_{j,s,t}$	curtailment of PVG active/reactive power at j
$P^{L,cur}_{j,s,t},Q^{L,cur}_{j,s,t}$	curtailment of load active/reactive power at j
$P^{PVG,cur}_{j,s,t},Q^{PVG,cur}_{j,s,t}$	curtailment of PVG active/reactive power at j
$P^{L,cur}_{j,s,t},Q^{L,cur}_{j,s,t}$	curtailment of load active/reactive power at j

Abbreviations

PG&E	Pacific Gas and Electric Company
DSP	distribution system planner
ADN	active distribution network
URN	uncertain random network
TSs	transformer substations
DGs	distribution generators
CBs	capacitor banks
SVCs	static var compensators
OLTCs	on-load tap changers
STs	spanning tree
WTG	wind turbine generator
PVG	photovoltaic generator
MST	minimum spanning tree
SOCP	second order cone programming
MISOCP	mixed-integer second order cone programming
DNP	distribution network planning
ANMs	active network managements
DSM	demand side management
ADNP	active distribution network planning
SOCR	second order cone relaxation
MINLP	mixed-integer nonlinear programming
CDF	cumulative distribution function
AU	average unavailability
AFVSI	average fast voltage stability index

operation and planning [1,8], the traditional distribution networks are undergoing the transformation from passive unidirectional flow networks to active distribution network (ADN) [9,10]. This transition introduces the enormous challenges to DSP in both economy and technology. As a system with controllable mechanism and flexible energies, the ADN technologies can provide significant solution to achieve the goal of system stability, reliability and sustainability, and this approach can be effectively used in wind and solar power application. On the other hand, the main active network management (ANM) schemes including demand side management (DSM), wind power curtailment, solar power curtailment, OLTC tap adjustment, continuous reactive power compensation, are proved to be able to decrease the operation costs and thus avoid unnecessary investment in active distribution network planning (ADNP) [11–13].