Energy 147 (2018) 451–463

Contents lists available at ScienceDirect

Energy

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

Information gap decision theory to deal with long-term wind energy planning considering voltage stability

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ARTICLE INFO

Article history:

Keywords:
Information gap decision theory (IGDT)
Loading margin uncertainty
Voltage stability
Wind energy
Wind energy planning (WEP)

ABSTRACT

This paper proposes a novel approach for long-term planning of wind energy considering its inherent uncertainty. The uncertainty of wind energy is handled via information gap decision theory (IGDT) method. Additionally, due to the importance of security considerations, loading margin is employed as an index of voltage stability to guarantee the security of power system. The operational constraints (such as power flow equations) in initial operation point considered along with those at the voltage collapse point, simultaneously. Accordingly, the IGDT-based voltage stability constrained wind energy-planning model is proposed that can be used for ensuring the safe operation of power networks. The main feature of this model is to handle the uncertainty of wind energy in the long-term wind energy planning via IGDT technique, by considering voltage stability constraints. In order to evaluate the capability of the IGDT technique for uncertainty handling of wind energy, the obtained results are compared with Monte Carlo simulations. To demonstrate the effectiveness of proposed model, it is applied to the New-England 39-bus test system. The obtained results validated the applicability of the proposed model for optimal wind energy planning. The proposed methodology could help wind farm investors to make optimal large-scale wind energy investment decisions.

1. Introduction

Due to serious concerns regarding the increasing environmental pollution caused by thermal generation units and risk issues of nuclear power generation, renewable energy sources have become superior energy to supply electricity demand. Among the renewable energy resources, wind power generation (WPG) has attracted the attention of power system operators and investors. On the other side, inappropriate planning of wind energy will pose power system to serious safety issues. One of the major barriers against high penetration of wind energy is the uncertainty associated with this renewable energy technology. Under such circumstances, the uncertainty associated with wind energy may cause some problems for wind farm (WF) owners' when they come to make investment decisions. The WPG uncertainty is one of the serious challenges that endangers the stability of power system, especially voltage stability which should be considered in planning stage of this type of renewable energy. Due to the importance of mentioned attractive concepts, researchers have worked on different dimensions of power systems under the influence of wind energy. In the following section, the existing literature is reviewed to build a backgrounds on voltage stability, wind energy planning (WEP) and uncertainty modeling of WPG.

Nowadays many power systems are operated very close to their voltage stability limits which will makes them vulnerable to voltage instability phenomena [1]. In this way, the concept of voltage stability has been investigated in different research works. The authors in Ref. [2], proposed a corrective voltage control scheme in order to guarantee the security of power system in normal and severe contingency conditions considering the desired loading margin. In Chang's work [3], the modal analysis method is used for optimal allocation of flexible ac transmission system in order to increase loading margin and decrease system expansion costs as a multi-objective problem. The voltage stability and reliability of power system were evaluated in different DG power generation scenarios [4]. The static and dynamic voltage stability analysis were carried out in Ref. [5], for planning of reactive power compensators in order to enhance the voltage stability of network with distributed wind energy generation. In Ref. [6], voltage stability and

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https://doi.org/10.1016/j.energy.2018.01.061
0360-5442/

Nomenclature

Sets

N_D	Demand levels in a year
D	Number of years for delay of investment
N_T	Planning horizon
NB_w	Proper buses for wind farm (WF) installation
NB	System buses
X	Set of all decision variables
NG	Thermal generating units
NL	Transmission lines

Indices

d	Demand levels index
t	Index of investment years
b	System buses index
l	Transmission lines index
i	Thermal generating units' index
W	WFs index

Variables and Parameters

$P^D_{b,t,d}/Q^D_{b,t,d}$	Active/reactive power load of bus b in year t and demand level d (per unit (pu))
$p^w_{b,t,d}/q^w_{b,t,d}$	Active/reactive power of WF w injected to bus b in year t and demand level d (pu)
$P^G_{i,t,d}/Q^G_{i,t,d}$	Active/reactive power generation by ith thermal generation unit in year t and demand level d (pu)
$\widehat{P}^D_{b,t,d}/\widehat{Q}^D_{b,t,d}$	Active/reactive power of load b in year t and demand level d.at VCP (pu)
$\widehat{P}^G_{i,t,d}/\widehat{Q}^G_{i,t,d}$	Active/reactive power generation by ith thermal generation in year t and demand level d at voltage collapse point (VCP) (pu)
MVA_{base}	Base power (MVA)
CF_{bc}	Capacity factor of WF in base case (BC)
CF	Capacity factor of WF
$\pi^w_{b,t}$	Cumulative wind power capacity of WF w connected to bus b up to year t (pu)
β	Critical value of profit to be maintained at presence of uncertainty in the RA strategy ($)
R_C	Critical/opportunistic percent of objective function used in risk averse strategy
$\varsigma_{b,t}$	Demand growth rate at bus b in year t
λ_{des}	Desired loading margin
G	Equality constraints
$WC^{\max}_t$	Forecasted installed capacity of WFs in year t (pu)
WFC_{inv}	Investment cost of WF ($/MW)
IFR	Inflation rate
ITR	Interest rate
H	Inequality constraints
$\lambda_{t,d}$	Loading parameter in year t and demand level d
$(P/Q)^{\max/\min}_{G_i}$	Maximum/minimum active/reactive power of ith thermal generation unit (pu)
$q^w_{b,\max/\min}$	Maximum/minimum reactive power of WF w injected to bus b (pu)
$V^{\max/\min}_b$	Maximum/minimum voltage in bus b (pu)
$S^{\max}_l$	Maximum transferable power through line l (pu)
Y_{bj}/ϕ_{bj}	Magnitude/angle of bj-th element of system admittance matrix (pu/rad)
$WFC_{O\&M}$	Operation and Maintenance cost of WF ($/MWh)
ρ	Penetration factor of wind energy
$\Im$	Profit of wind energy selling ($)
$\Im_{bc}$	Profit of wind energy selling in BC ($)
$S_{l,t,d}(V,\theta)$	Power flow through lth transmission line in year t and demand level d (pu)
$K_{G,i}$	Rate of change in active power generation of ith thermal generation unit
$K_{D,b}$	Rate of load change at bus b
T^h_d	Total number of hours in a year in demand level d (hours)
$P^w_{b,t}$	The added wind power capacity for WF w connected to bus b in year t (pu)
α	Uncertainty radius of uncertainty parameter
$\mathscr{L}$	Uncertainty parameter
U	Uncertainty set
$V_{b,t,d}/\theta$	Voltage magnitude/angle of bus b in year t and load level d (pu/rad)
$\widehat{V}_{b,t,d}/\widehat{\theta}_{b,t,d}$	Voltage magnitude/angle of bus b in year t and load level d.at VCP (pu/rad)
EP_d	Wind energy price ($/MWh)

reactive power losses were simultaneously optimized as a multi-objective problem and best compromise solution was selected via fuzzy satisfying approach. The author of [7], proposed a methodology to find the critical transmission lines and rate of power that could be injected to the grid by series compensations in order to increase loading margin of the network.

Several constraints have been considered in WEP literature. For example, the operational constraints considered for planning of wind energy in Ref. [8]. Also, Author of [9] proposed two optimization algorithms for planning of wind energy, while market constraints were considered as well in planning model. Furthermore, in Ref. [10], important factors for planning of wind energy were investigated and reviewed from different planning aspects.

Several methods for uncertainty modeling of input parameters have been developed such as Information gap decision theory (IGDT) [11], Monte Carlo simulations (MCS) [12], point estimate method [13], scenario based modeling [14], fuzzy logic [15] and robust optimization [16]. In Soroudi's work [17], the uncertainty associated with investment and operation of WFs from the distributed generation operators'/owners' perspective carried out by hybrid possibilistic-probabilistic method in order to assess the impact of wind energy generation units on technical performance of distribution network. Also, the authors in Ref. [18] proposed a risk averse decision making tool for preventive voltage control of joint AC/DC power systems taking into account the uncertainty of wind energy and load demand. Conditional value at risk is utilized as the risk measure and the uncertainties were modeled via scenario-based approach. The power losses are decreased as a result of integration of wind power of WFs in Ref. [19], where optimal allocation of WFs is obtained via hybrid optimization method. The MCS is combined with two other optimization method to model the uncertainty of WFs and loads existing in the network.

Among the uncertainty modeling techniques, the IGDT is one of the practical methods that can be used for handling the uncertainty of wind energy to avoid problem caused by this phenomena. This method has specific properties that make it superior. For example, in comparison to stochastic techniques, this method does not need information of probability density function of uncertain parameter.