Applied Energy 122 (2014) 62–72

Contents lists available at ScienceDirect

Applied Energy

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

A statistical cognitive model to assess impact of spatially correlated wind production on market behaviors

Morteza Rahimiyan *

Department of Electrical Engineering, University of Shahrood, Shahrood 3619995161, Iran

HIGHLIGHTS

- Statistical cognitive model simulates the impact of wind production on market power.
- Market simulation without considering the exercise of market power may not be realistic.
- Statistical cognitive model considers producers' ability to exercise the market power.
- The spatial correlation among wind farms can affect the exercise of market power.
- The spatial correlation among wind farms can affect significantly the price variability.

ARTICLE INFO

Article history:
Received 13 May 2013
Received in revised form 31 January 2014
Accepted 4 February 2014
Available online 28 February 2014

Keywords:
Wind power uncertainty
Spatial correlation
Statistical cognitive model
Electricity market

ABSTRACT

Over the last decade, the share of wind power production has rapidly increased. Thus, the market clearing outcomes have been exposed by inherent power production uncertainty of wind farms. This uncertainty may inevitably affect the behaviors of strategic producers in exercising their market power. In this paper, a statistical cognitive model is proposed to simulate the strategic behaviors in presence of the wind power uncertainty. To this end, an approach based on Copula theory is used to characterize wind power uncertainty considering spatial correlation among diverse wind farms. Moreover, the proposed cognitive model allows strategic producers to learn how to exercise their market power.

1. Introduction

1.1. Aim and approach

Over the last decade, the share of wind power production has rapidly increased. Thus, the market clearing outcomes have been exposed by inherent power production uncertainty of wind farms. This uncertainty may inevitably affect the behaviors of strategic producers in exercising their market power. In addition, as it is well-known, a spatial correlation may exist among diverse wind farms [1]. Within the context above, this paper addresses how the market behaviors are changed by different levels of wind power uncertainty as well as potential correlation among wind farms.

In general, the electricity markets experience different levels of market power exercised by different agents. However, the competition level among diverse producers depends on the characteristics of generation, demand and network (e.g., the distribution of generating units among producers and buses), the market architecture (e.g., the trading floors considered) and the market polices (e.g., the pricing mechanism). As the wind uncertainty naturally changes the generation characteristics, it may affect the level of potential market power and thus the strategic behaviors. Therefore, to gain more realistic insight into the impacts of the wind uncertainty, the market power exercised by diverse agents needs to be re-evaluated.

In this paper, a statistical cognitive model is proposed to assess the impact of wind uncertainty on market behaviors in a pool-based day-ahead market. This approach can also be useful for a market regulator to anticipate the potential consequences of its regulatory policies, which is crucial in making informed policy decisions.

Within the proposed statistical cognitive model, a set of wind power scenarios are generated using Copula theory which enables us to consider the spatial correlation among diverse wind farms. Note that we consider the wind power production as a negative random load. Then, a profit-maximization problem is solved per strategic producer using a learning algorithm. This algorithm derives offering decisions of each producer without knowledge

* Tel./fax: +98 273 3300250.
E-mail address: morteza.rahimiyan@shahroodut.ac.ir

http://dx.doi.org/10.1016/j.apenergy.2014.02.004
0306-2619/

List of symbols

Parameters

a	action taken by agent
B	nodal susceptance matrix
C^{D}/B^{D}	diagonal matrix of slope/vector of intercept associated with consumers' bid function
C^{G}/B^{G}	diagonal matrix of slope/vector of intercept associated with producers' offer function
C^{M}/B^{M}	diagonal matrix of slope/vector of intercept associated with producers' marginal cost
H	diagonal matrix of lines susceptance
I	branch-node incidence matrix of network
$P^{DB,\max}$	vector of maximum load levels for consumers
$P^{GO,\min}$	diagonal matrix of minimum generation limits offered by producers
$P^{GO,\max}$	diagonal matrix of maximum generation limits offered by producers
$P^{G,\min}$	diagonal matrix of actual minimum generation limits for producers
$P^{G,\max}$	diagonal matrix of actual maximum generation limits for producers
$P^{L,\max}$	vector of maximum flow limits of lines
$Q(s,a)$	Q-value for state-action pair (s,a)
s	state of environment
R/ρ	matrix/scalar coefficient of product moment correlation
R_r/ρ_r	matrix/scalar coefficient of rank correlation
$\Delta Q(s,a)$	Variation of Q-value for state-action pair (s,a)

Random variables

$P^{W,\max}$	vector of available wind power productions
WS	vector of wind speeds

Variables

P^{D}	vector of load levels
P^{G}	vector of power productions
P^{W}	vector of wind power productions injected into the network
V	vector of binary variables (0/1) to show the commitment status of generating units
δ	vector of voltage angles

Functions

$F_{X_i}(\cdot)$	cumulative distribution function of random variable X_i
$F_{X_i,X_j}(\cdot)$	joint cumulative distribution function of random variables X_i and X_j
$r(\cdot)$	immediate reward that an agent receives
$\Phi_{N_i}(\cdot)$	standard normal cumulative distribution function of random variable N_i

on the ones of rival producers. In the next step, according to given load, each wind power scenario, offering decisions of producers and network constraints, the market is cleared. The above market clearing procedure is repeated for all wind power scenarios considered. Finally, the impact of the wind power uncertainty on the market behaviors is analyzed through some statistical parameters.

1.2. Literature review and contributions

A variety of works are available in the technical literature to study the potential impacts of wind production on supply cost in UK [2], operation cost in US [3], price differences among four ERCOT zones in Texas [4], and clearing outcomes of Danish market [5,6].

To gain comprehensive insight into wind production impacts, we certainly need a simulation tool with the ability of altering the technical/economic characteristics of a power system, e.g., the realizations of wind power production, the generation mix, and the regulatory mechanisms. In this vein, a non-parametric regression model is developed in [7] to capture how the expected spot price is affected by the accuracy of wind power forecasts. Furthermore, [7] verifies that the wind forecasts may affect the distribution of prices significantly. In [8], the impacts of wind penetration level, wind location and its generation control strategies on the single-auction prices and the total generation costs are analyzed. However, the variability nature of wind production is not considered.

In [9,10], two recently developed scenario generation techniques are used to study the effects of the correlated wind power productions on the market clearing outcomes under a competitive setting. In [9], a simulation tool is presented to analyze the impact of wind production uncertainty on locational marginal prices (LMP). In [10], the future effects of European wind power expansion on operation of Swiss network are studied.

It is worthy to indicate that the conventional scenario generation techniques usually apply the well-known joint distribution functions (e.g., normal) to the actual domain of wind data. The drawback of such conventional techniques is that the wind data (i.e., wind speed or wind power) may not be actually modeled through a specified distribution function. To overcome such a drawback, the advanced scenario generation techniques have been developed, whose contribution is to apply the well-known distribution functions to the domain of *transformed* wind data. For example, in [9,11,12], a normal Cumulative Distribution Function (CDF) is used to transform the wind data into normal domain. Another drawback of the conventional scenario generation techniques is that due to the complexity issues of wind nature, the product moment correlation fails to model the nonlinear correlation of wind data. One possibility to overcome both drawbacks aforementioned is to use Copula theory, as one of advanced scenario generation techniques, which has been recently implemented in modeling stochastic generation in power system [1,10,13].

Similar to the aim of this paper, the diverse potential impacts of wind power uncertainty on market behaviors of an oligopoly are studied in the literature using either mathematical [14,15] or agent-based models [16]. In [14], a theoretical approach is proposed to compare duopoly prices (considering option and forward contracts) with monopoly ones. In this reference, the wind production is simply modeled via uniform distribution. In [15], a supply function equilibrium model is used to analyze how the variability of wind production may affect the UK electricity prices in a future year (i.e., 2020). This long-term study concludes that the duopoly prices and their variability are comparatively greater than those in a competitive case. In [16], an agent-based model is used to study how different levels of wind power penetration may affect the producers' strategic behaviors in German electricity market. Note that in [14–16], the stochastic dependency among wind farms of a region is not explicitly modeled.

Note that both mathematical and agent-based models have been extensively used in the literature. Regarding their characteristics, it is important to note that unlike mathematical models which analytically derive a relationship among the players' strategic behaviors, the agent-based models provide a numerical tool for