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Impact of spatio-temporal correlation of wind production on clearing outcomes of a competitive pool market

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ABSTRACT

By the increase of wind power penetration in electricity markets, a relevant issue is how correlated power production of diverse wind farms may change market clearing outcomes. This paper uses real-world historical wind data to capture spatio-temporal correlation among diverse wind farms. In a simulation framework, we evaluate statistically impact of correlated wind production on clearing outcomes of a competitive pool market, while incorporating inter-temporal constraints of dispatchable generating units to market clearing model. This allows to address how such constraints and associated costs may change the impact of correlated wind production. The market clearing outcomes are statistically evaluated for different levels of spatio-temporal correlation of wind production in the cases with and without inter-temporal constraints. This numerical evaluation is run for different load profiles to examine how technological diversification of dispatchable generating units may change the impact of correlated wind production. An illustrative example and a case study show results and conclusions.

1. Introduction

1.1. Motivation and aim

By the increase of wind power penetration in electricity markets, a relevant issue is how correlated power production of diverse wind farms may change market clearing outcomes.

The interdependence structure of wind power production, in both time and space, is dynamic and complex [1]. The wind power production may temporally depend on time series of historical wind data. Moreover, the power productions of close wind farms may be spatially correlated. An important observation is that such a spatio-temporal correlation can affect the pattern of wind power production, and resulting consequences within electricity market.

As the pool market is an attractive choice for the wind producers, the market clearing outcomes are substantially coupled with dynamically changing wind production. In this condition, commitment status of some dispatchable generating units may change dynamically over time to accommodate the time-variant wind power production. In this respect, the working of the generating units is different due to technological diversification. The operational capability and flexibility of such units for handling the wind variability are mainly characterized by their inter-temporal constraints (ITCs) and associated costs. Within this context, a key issue is how the ITCs of generating units may change the impact of wind power production on the market clearing outcomes.

This paper aims to analyze the impact of correlated wind power production as well as the ITCs of dispatchable generating units on the clearing outcomes of a competitive pool-based day-ahead electricity market. To this end, the market clearing problem is mathematically modeled as Mixed-Integer Linear Programming (MILP) problem. This model accounts the ITCs and associated costs of dispatchable generating units. In addition, a statistical methodology is used to generate correlated scenarios of the wind power production considering the spatio-temporal correlation among diverse wind farms. The market clearing problem is solved for each correlated scenario. Finally, the clearing outcomes such as energy prices and operational behavior of dispatchable generating units are statistically evaluated.

1.2. Literature review

As the wind power penetration is rapidly increasing in electricity industry, a variety of empirical studies have investigated

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Nomenclature

Parameters

- b_{nm} susceptance value of line (n, m)
- $f_{ij}^{G}(h)$ offer price of block j of generating unit i in hour h
- $f_{k}^{W}(h)$ offer price of wind farm k in hour h
- $H_{i}^{ON/OF}$ number of hours during which generating unit i must be online/offline at the beginning of time horizon
- $H_{i}^{UP/DO}$ minimum up/down time of generating unit i
- NH number of hours in time horizon
- $p_{b}^{D}(h)$ power load at bus b in hour h
- $p_{i}^{G,max}(h)$ upper generation limit of generating unit i in hour h
- $p_{i}^{G,min}(h)$ lower generation limit of generating unit i in hour h
- $p_{ij}^{G,max}(h)$ capacity of block j of generating unit i in hour h
- $p_{nm}^{L,max}$ maximum flow limit of line (n, m)
- R_{i}^{UP}/R_{i}^{DO} ramp up/down limit of generating unit i
- suc_i/sdc_i start up/shut down cost of generating unit i

Random variable

- $p_{k}^{W,max}(h)$ available wind power production of wind farm k in hour h
- $WS_k(h)$ wind speed of wind farm k in hour h

Variables

- $p_{k}^{W}(h)$ wind power production of wind farm k in hour h
- $p_{ij}^{G}(h)$ power production of block j of generating unit i in hour h
- $p_{i}^{G}(h)$ power production of generating unit i in hour h
- $p_{nm}^{L}(h)$ power flow through line (n,m) in hour h
- $u_i(h)$ binary variable to show on/off status of generating unit i in hour h
- $vsuc_i(t)$ auxiliary variable to present start up cost of generating unit i in hour h
- $vsdc_i(t)$ auxiliary variable to present shut down cost of generating unit i in hour h
- $\delta_b(h)$ voltage angle at bus b in hour h

Sets

- Ω^{B} set of buses.
- Ω^{L} set of lines
- $\Omega_{b}^{G}/\Omega_{b}^{W}$ set of generating units/wind farms located at bus b

Functions

- $F_{WS_k}(.)$ empirical cumulative distribution function of historical wind speed in wind farm k
- $\phi_N(.)$ standard normal cumulative distribution function

different impacts of the wind power production on the outcomes of electricity markets. The interaction between wind energy sources and energy prices is analyzed in Dutch [2], Ontario [3], German–Austrian [4], and Texas [5]. In Ref. [6], robust econometric models and a statistical inference are used to assess benefits obtained from the wind power production in PJM day-ahead market. In Ref. [7], potential impact of the wind power production on the reduction of market prices and energy produced from gas and coal power plants in Australian national electricity market is examined. In Ref. [8], flexibility of dispatchable generating units to respond the variation of wind power production and load in German electricity market is assessed for a long-term horizon. In Ref. [9], performance of renewable electricity support schemes in Spanish electricity market is evaluated. In Ref. [10], technical challenges of large-scale wind integration in European electricity industry are reviewed. Furthermore, the efficiency of several possible options (e.g., increasing the spatial distribution of wind energy sources, deploying additional power reserve and expanding the power grid) to accommodate the wind power production is investigated.

While the empirical studies above can reveal ex-post impacts of the wind power production, simulation tools are required to carry out ex-ante analysis of the market outcomes before actual realization. Compared to the existing empirical reports, the simulation studies have rarely focused on this topic. To clarify the background of challenges and findings addressed in this paper, the technical literature of simulation studies can be categorized based on whether the correlation of wind power production is considered or not.

One category studies the market impacts of wind power production without considering such correlation [11–13]. It is worthy to note that the main contribution of these references lies on the modeling of energy markets with wind power integration, however the wind power uncertainty is simply modeled. In Ref. [11], the behavior of UK electricity market is simulated in target year 2020. Energy prices and revenues are analyzed with respect to penetration level and variability of the wind production. In Ref. [12], a pricing scheme is proposed for a pool market that includes a significant number of wind producers. Moreover, the potential benefits that can be obtained from it are numerically analyzed. In Ref. [13], the equilibrium of an oligopolistic pool market in presence of large-scale wind integration is modeled as equilibrium problem with equilibrium constraints. The simulation results reveal that wind spillage and profit gained by dispatchable units may increase in higher levels of wind penetration.

Another category models correlated wind power production based on 1) temporal correlation structure [14–20], 2) spatial correlation structure [21–25], and 3) spatio-temporal correlation structure [26,27]. In this vein, we find that the technical reports address the market impact of correlated wind production from two prevailing perspectives. One view focuses on modeling wind correlation in wind power forecast and assessing the market impacts of forecast accuracy. Another one focuses on developing probabilistic models which allow to characterize inherent variability of correlated wind power production, and to quantify statistically its resulting consequences within the electricity market.

Temporal correlation studies: In Ref. [14], performance of persistent and Grey predictors for short-term forecast of the wind power production is compared, and impact of the wind power volatility and the forecast accuracy on market prices is evaluated. The results demonstrate that improvement of the wind forecast accuracy does not necessarily result in more accurate market prices. In Ref. [15], an agent-based modeling approach is adopted to simulate day-ahead electricity market. Within this computational laboratory, impact of short-term wind forecast accuracy as well as wind penetration level on market prices and net revenues of the wind producers is assessed. The results show that the application of more accurate wind forecast method is effectively beneficial to increase the net revenues of the wind producers. In Ref. [16],