Electric Power Systems Research 141 (2016) 372–380

Contents lists available at ScienceDirect

Electric Power Systems Research

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

A high-performance computing framework for analyzing the economic impacts of wind correlation

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ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form 18 July 2016
Accepted 7 August 2016
Available online 6 September 2016

Keywords:
Covariance estimation
Correlation
Economic dispatch
Stochastic optimization
Wind power

ABSTRACT

We analyze the impact of capturing spatiotemporal correlations between wind supply points on grid dispatch procedures. We first show analytically that over/underestimation of correlation leads to non-intuitive cost biases. A detailed computational study for the U.S. state of Illinois grid reveals similar conclusions. Our computing framework combines a stochastic dispatch formulation with correlation information derived from a Rao-Blackwell-Ledoit-Wolf estimator. The estimator approximates the covariance matrix from a small number of expensive wind ensembles generated with a numerical weather prediction model. The prediction model is validated with real meteorological data to obtain realistic correlation information. The resulting stochastic dispatch problems are solved with the parallel interior-point solver PIPS-IPM on the BlueGene/Q (Mira) supercomputer at Argonne National Laboratory. We use the correlation information to generate a larger set of scenarios and implement a fast inference analysis capability to assess the accuracy of the system cost. We demonstrate that the computing framework enables sophisticated system-wide analyses that can be performed in minutes (as opposed to days if computations would be performed in serial). We find that strong and persistent biases result from neglecting correlations and conclude that coordinating uncertainty characterizations for wind power producers is necessary. The framework is also used to quickly assess the impact of operating the grid under different correlation strengths. Our work seeks to highlight the scope of modern high-performance computing systems and computational optimization tools.

Published by Elsevier B.V.

1. Introduction

Achieving efficient grid operations in the presence of intermittent renewable power is a challenge because these supply sources follow complex spatiotemporal patterns (see Fig. 1) that extend over wide geographical regions (e.g., tens to hundreds of kilometers) and long periods of time (i.e., hours to days). Reserve allocation procedures therefore can be ineffective, and more adaptive and systematic approaches based on stochastic and robust optimization techniques are needed.

Stochastic and robust optimization techniques rely on uncertainty characterizations. Correlation (or covariance) information, in particular, is key because this guides forecast aggregation/disaggregation procedures and because it is needed to characterize risk in dispatch cost and revenues of market players. For instance, if the supply of a wind farm in a region is uncorrelated from that in another region, these can be forecasted independently without affecting dispatch cost. When correlations exist, however, one would expect that using independent forecasts will introduce errors in the uncertainty characterization and this will bias dispatch cost and shift incentives of the players (wind power suppliers, distributors, and consumers).

This situation was hypothesized in the stochastic economic dispatch setting of Pritchard and coworkers [1] (see Section 5). In Xie et al. [2] such biases seem to occur in day-ahead reliability unit commitment and robust look-ahead economic dispatch models because of differences in the correlations given by different estimation techniques. Also, Ghofrani et al. [3] identify wind correlation as a determining factor in choosing wind sites and find empirically that it considerably impacts the reserve requirements and network congestion. The present study is, to the best of our knowledge, the first to address the issue of such cost biases and to offer a magnitude

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http://dx.doi.org/10.1016/j.epsr.2016.08.010
0378-7796/Published by Elsevier B.V.

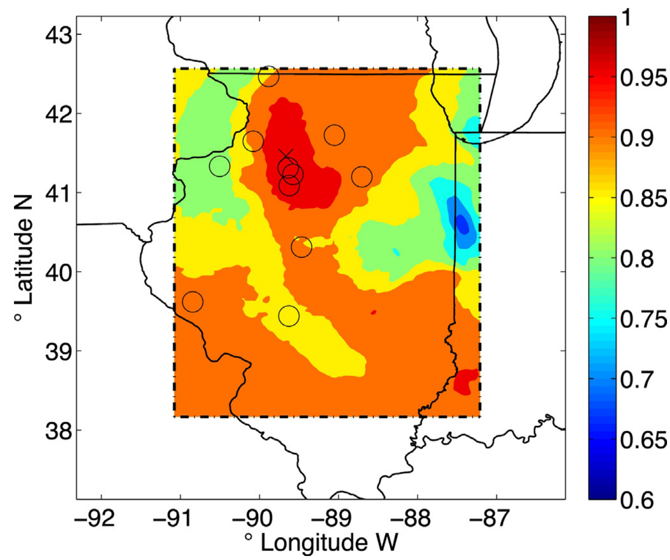

Fig. 1. Spatial correlations for wind speed in the State of Illinois with respect to the location indicated by "×". The locations indicated by circles depict actual wind farms.

of the cost gaps that occur in realistically sized economic dispatch systems.

From a market implementation point of view, determining long-range correlations is a challenge because wind farm or solar power plant owners might not be willing to share their forecasting procedures and their site information with other markets players and the ISO. Consequently, they might prefer to construct their own forecasts and uncertainty levels, possibly neglecting correlations with other sites. Owners might also need to ignore long-range correlations because of computational limitations faced by their forecasting vendors. Computational challenges arise because properly resolving the space-time features of numerical weather prediction (NWP) systems requires significant computational power [4], and few computing sites exist in the world that can obtain forecasts that accurately capture both short-range conditions at the supply site and long-range behavior. When trying to properly characterize uncertainty and its correlation structure this points to the need both for a wide-area forecasting approach and for accommodating computational limitations.

Properly designing decentralized markets that factor in uncertainty in weather-driven supply is necessary, but this requires significantly more complex information exchange mechanisms between the ISO and market players compared with existing deterministic settings [1,5]. To design such information exchange mechanisms, one needs to understand the effects that certain information has on performance. In this work, we study the effect of long-range correlation information on dispatch cost in the presence of wind power. We first present an analytic example to prove that correlation between suppliers' output can positively or negatively bias dispatch cost in non-intuitive ways (depending on the correlation direction). We then perform a detailed computational study using a stochastic economic dispatch setting in the Illinois transmission system. We use validated wind speed ensemble forecasts obtained with the NWP system WRF that are propagated through typical wind power curves in order to obtain wind power ensembles. We use the Rao-Blackwell-Ledoit-Wolf estimator to generate scenarios from the limited number of WRF samples available to perform inference analysis and refine the cost estimates.

Our computational study reveals that significant dispatch cost biases that would scale up to an order of hundreds of millions of dollars a year (if similar correlation patterns across the year hold) can be introduced by ignoring long-range correlation. We also show that confidence levels of dispatch cost differ significantly from the actual ones when correlations are neglected. In our study, the confidence intervals when ignoring correlations were narrower, thus underestimating the number of scenarios necessary to close the cost gap due to stochastic approximation of the wind uncertainty. From a market design perspective our study thus indicates that, as hypothesized in the stochastic market setting of [1], centralized forecasts that can properly account for correlations are superior to localized ones when used for constructing wind power bids by suppliers in markets with significant wind power penetration. This points to the need of coordinating forecasts and uncertainty characterizations in order to capture long-range correlations among power producers. Neglecting such correlations (e.g., by allowing producers to provide their own uncertainty characterizations) can introduce cost and price biases.

Diverse studies on the impact of wind correlation on power system operations have been reported in the literature. In [6] the authors propose a market clearing model and find that spatial correlations can have significant effects on locational marginal prices. In [7] the authors find that spatio-temporal correlations can drastically increase risk to consumers if wind farms are not dispersed enough. In [8] the authors propose a stochastic optimal power flow conclude that correlations can also alter reactive power. The studies available in the literature use simplified case studies based on IEEE test models and historical data sets. To the best of our knowledge, the analysis proposed in this work is the most sophisticated study reported in the literature on the effects of wind power correlation. In particular, our analysis combines advanced numerical weather prediction models (that have been validated with meteorological information), large-scale power system network models, stochastic market clearing formulations, parallel optimization solvers, advanced covariance estimation schemes, and inference analysis techniques. We combine these tools in a high-performance computing platform to enable sophisticated analyzes in minutes. Performing such analyzes on a standard serial computer would have taken days. Our work seeks to highlight the scope of modern high-performance computing systems and computational optimization tools.

The paper is structured as follows. In Section 2 we present a motivating example to illustrate the effect of correlation information on dispatch cost. In Section 3 we present a detailed computational study using data for the state of Illinois transmission system. This section describes the dispatch model, the scenario generation procedure, the covariance estimator, and the numerical results. Section 4 presents concluding remarks.

2. Motivating analytical example

Consider a single-node system with three suppliers and one consumer. Two suppliers, G_1 and G_2, have uncertain power output and the outputs follow Gaussian distributions, $\mathcal{N}(w_1, \sigma_1)$ and $\mathcal{N}(w_2, \sigma_2)$. We define $\rho \in [-1, 1]$ as the correlation coefficient and assume that both suppliers have a cost p_w. The third supplier, G_3, is assumed to be deterministic, supplies power at cost p_{th} with $p_{th} > p_w$ and has infinite capacity. The demand quantity d, is assumed to be deterministic and inelastic.

By construction, one can deduce that as much cheap power as possible should be produced. If this does not satisfy all demand, then G_3 will be dispatched to fulfill the remaining demand. Consequently, the negative dispatch cost is $c_d = \mathbb{E}[p_w \min(X_1 + X_2, d) + p_{th} \max(d - X_1 - X_2, 0)]$. Furthermore, to derive the dependence $c_d = c_d(\rho)$, we write