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Electricity market clearing with improved scheduling of stochastic production

Juan M. Morales [a,*], Marco Zugno [a], Salvador Pineda [b], Pierre Pinson [c]

[a] Department of Applied Mathematics and Computer Science, Technical University of Denmark, Kgs. Lyngby, Denmark
[b] Department of Mathematical Sciences, University of Copenhagen, Copenhagen, Denmark
[c] Department of Electrical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark

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ABSTRACT

In this paper, we consider an electricity market that consists of a day-ahead and a balancing settlement, and includes a number of stochastic producers. We first introduce two reference procedures for scheduling and pricing energy in the day-ahead market: on the one hand, a conventional network-constrained auction purely based on the least-cost merit order, where stochastic generation enters with its expected production and a low marginal cost; on the other, a counterfactual auction that also accounts for the projected balancing costs using stochastic programming. Although the stochastic clearing procedure attains higher market efficiency in expectation than the conventional day-ahead auction, it suffers from fundamental drawbacks with a view to its practical implementation. In particular, it requires flexible producers (those that make up for the lack or surplus of stochastic generation) to accept losses in some scenarios. Using a bilevel programming framework, we then show that the conventional auction, if combined with a *suitable* day-ahead dispatch of stochastic producers (generally different from their expected production), can substantially increase market efficiency and emulate the advantageous features of the stochastic optimization ideal, while avoiding its major pitfalls.

A two-node power system serves as both an illustrative example and a proof of concept. Finally, a more realistic case study highlights the main advantages of a smart day-ahead dispatch of stochastic producers.

1. Introduction

The penetration of stochastic production in electric energy systems is notably increasing worldwide, primarily owing to a booming wind power industry. There is a broad consensus in the research community that today's electricity market designs are to be revisited so that stochastic producers can enter the competition in a fair and efficient manner.

In its most basic form, an electricity market consists of a forward (typically day-ahead) market and a balancing market. On the one hand, the day-ahead market is required to accommodate the generation from the *inflexible* power plants, i.e., from those generating units that need advance planning in order to efficiently and reliably set their production levels. On the other, the balancing market clears the energy deployed to maintain the constant balance of supply and demand over periods of time with finer resolution, commonly spanning from minutes to one hour. Being cleared shortly before real time, balancing markets allow the trade of energy between *flexible* firms, which can adjust their output quickly, and stochastic producers, whose generation is predictable only with limited accuracy at the day-ahead stage.

Conventionally the day-ahead and the balancing markets are settled independently. Furthermore, with respect to the participation of stochastic producers, the day-ahead market is typically cleared considering their expected production at a very low marginal cost (e.g., zero). The eventual energy adjustments needed to cope with the associated forecast errors are left then to the flexible units participating in the balancing market. Consequently, if this market is not provided with enough flexible capacity, balancing costs may escalate dramatically. It is expected that this problem becomes exacerbated as the penetration of stochastic production increases (Holttinen, 2005; Doherty & O'Malley, 2005; Helman et al., 2010).

To face this challenge, two main solution strategies have been considered, namely:

1. To establish reserve markets, where flexible capacity is procured sufficiently in advance of energy delivery and then made available to the balancing market, where it is dispatched if needed. The reserve demand in these markets is *exogenously* specified by the Transmission System Operator, which opens up a number of different ad hoc criteria, see e.g. Ela, Milligan, and Kirby (2011).

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* Corresponding author. Tel.: +45 45253428.

E-mail addresses: jmmgo@dtu.dk (J.M. Morales), mazu@dtu.dk (M. Zugno), s.pineda@math.ku.dk (S. Pineda), pp@dtu.dk (P. Pinson).

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2. To clear the forward market using stochastic programming (Birge & Louveaux, 2011), which allows modeling future balancing needs and costs in a probabilistic framework, thus yielding the day-ahead energy dispatch that minimizes the expected system operating costs. One of the major advantages of this approach is that it *endogenously* solves for the optimal amount of reserve capacity to be left to the balancing market, weighing the expected costs and benefits of such capacity (Galiana, Bouffard, Arroyo, & Restrepo, 2005; Bouffard & Galiana, 2008; Morales, Conejo, & Pérez-Ruiz, 2009; Papavasiliou, Oren, & O'Neill, 2011).

Ideally, the stochastic solution method attains maximum market efficiency (as it minimizes the expected system operating cost) and therefore, it is used here as a reference in this respect. For its practical application within a market environment, though, it must be first complemented with a set of prices and payments that make market participants satisfied with the resulting day-ahead dispatch. In this vein, Galiana et al. (2005) and Wong and Fuller (2007) define prices for both energy and reserve capacity. However, determining who should pay for such reserve and to which extent is still a major source of conflict and debate (Hogan, 2005).

In this paper, we follow the approach of Pritchard, Zakeri, and Philpott (2010) and Morales, Conejo, Liu, and Zhong (2012), where the stochastic dispatch is supported by energy prices only. However, this approach is not without its problems either. Indeed, Morales et al. (2012) illustrate that the energy-only market settlement associated with the stochastic dispatch requires flexible producers to accept losses for some realizations of the stochastic production, which also raises concerns on its practical applicability.

Starting from this point, the objective of this paper is to show that, if cleared with an appropriate value of stochastic production, *generally different from the expected value*, the conventional settlement of the day-ahead market can notably approach the behavior of the ideal stochastic dispatch, while sidestepping its theoretical drawbacks. For this purpose, we construct a bilevel programming formulation that determines the *optimal* value of stochastic production that should be used to clear the day-ahead market under the conventional settlement.

The rest of this paper is organized as follows. Section 2 presents the conventional and stochastic dispatch models that we use as references in our work, and provides the mathematical insight to calculate the optimal day-ahead schedule of stochastic production under the conventional market settlement. Section 3 discusses results from a small example and a case study. More specifically, the example serves to illustrate the different dispatch models, which are subsequently compared and tested using a more realistic setup in the case study. Lastly, Section 4 concludes the paper.

2. Dispatch models

Consider the sequence of a day-ahead and a balancing market. The day-ahead market is cleared on day $d-1$ (e.g., by 10 am) and covers energy transactions for delivery on day d, typically on an hourly basis. The balancing market settles the energy imbalances with respect to the day-ahead production and consumption schedule. These imbalances are computed throughout day d, usually over time intervals ranging from minutes to 1 h.

Let us begin by outlining a standard model for the dispatch of energy. This will serve to present the notation and provide a starting point for the developments of the rest of the paper. The setting will be an electric power system comprising a collection N of nodes.

2.1. Conventional dispatch (ConvD)

Let p_G and p_W denote the vectors of decisions on the day-ahead dispatch of conventional and stochastic producers, respectively. For simplicity and without loss of generality, the demand at each node n of the system, l_n, is considered to be known with certainty. As we will clarify later, though, the following discussion also holds in the case that demand is elastic or uncertain, provided that the dispatch model below is linear. We also assume that power flows in the transmission network are determined by the vector δ^0 of nodal voltage angles.

The conventional economic dispatch model (ConvDM) identifies the optimal schedule (p_G^*, p_W^*) that minimizes day-ahead generating costs, $\mathcal{C}^{\mathrm{D}}(p_G, p_W)$, as follows:

$$\underset{p_G,\ p_W,\ \delta^0}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{D}}(p_G,\ p_W) \tag{1a}$$

$$\text{s.t.} \quad h^{\mathrm{D}}(p_G, p_W,\ \delta^0) - l = 0 : \lambda^{\mathrm{D}}, \tag{1b}$$

$$g^{\mathrm{D}}(p_G,\ \delta^0) \leqslant 0, \tag{1c}$$

$$p_W \leqslant \widehat{W}, \tag{1d}$$

where $\widehat{W}$ is the forecast vector of stochastic production. The equality constraints (1b) enforce the day-ahead balancing conditions, stating that the dispatch plus the net power flow equals the demand at each node. The inequalities (1c) include upper and lower bounds to the dispatch of conventional producers and scheduled power flows, as well as declarations of non-negative variables. Constraints (1d) limit the day-ahead schedule of stochastic producers to their expected generation.

The dispatch model (1) can be understood as a network-constrained auction that follows a least-cost merit-order principle, i.e., the cheapest generators are dispatched first. Consequently, because stochastic producers enter the market with very low or zero marginal cost, their dispatch up to the forecast mean $\widehat{W}$ is prioritized (provided that the network allows for it). Note that we have intentionally made the cost function $\mathcal{C}^{\mathrm{D}}(\cdot)$ in (1a) dependent on p_W to cover the more general case in which the marginal cost of stochastic production is considered different from zero.

Notice that the vector of dual variables associated with constraint (1b), which is indicated in (1) by λ^{D}, constitutes the vector of day-ahead locational marginal prices.

Once the optimal day-ahead schedule $(p_G^*,\ p_W^*)$ has been obtained from (1), the balancing market must deal with the energy imbalance caused by the stochastic production. Consider a specific realization vector of this production, denoted by $W_{\omega'}$. The energy imbalance is then given by $W_{\omega'} - p_W^*$, which represents a surplus of generation, if positive, or a shortage, if negative. To accommodate an excess of production, several actions may be taken, namely:

- To decrease the power production of flexible generating units. In market terms, this is equivalent to say that flexible producers repurchase a certain amount $r_{\omega'}^-$ of energy in the balancing market.
- To spill a part $W_{\omega'}^{\text{spill}}$ of the stochastic production.

Similarly, to balance a deficit of generation, the following actions may be taken:

- To increase the power output of flexible units, which is equivalent to say that flexible producers sell an additional amount $r_{\omega'}^+$ of energy in the balancing market.
- To shed a portion $l_{\omega'}^{\text{shed}}$ of the demand. This action is, in general, very costly, as the so-called *value of lost load* is normally very high.