# Redefining the Merit Order of Stochastic Generation in Forward Markets

Juan M. Morales, *Member, IEEE*, Marco Zugno, *Student Member, IEEE*, Salvador Pineda, *Member, IEEE*, and Pierre Pinson, *Senior Member, IEEE*

***Abstract*—This letter proposes a new merit order for the dispatch of stochastic production in forward markets (e.g., day-ahead markets). The proposed merit order considers not only the marginal cost of the stochastic generating unit, which is often very low or zero, but also the projected cost of balancing its energy deviations during the real-time operation of the power system. We show, through an illustrative example, that the proposed merit order leads to increased market efficiency as the penetration of stochastic generation in the electricity market grows.**

***Index Terms*—Merit order, renewable energy, stochastic generation, stochastic programming, bilevel programming.**

## I. Introduction

The contribution of renewables to the electricity supply, in particular of wind and solar energy, is remarkably increasing worldwide [1]. While being environmentally friendly, these renewable generation technologies are weather dependent and therefore, inherently stochastic, i.e., their power production cannot be predicted with 100% accuracy. Today's electricity markets were not designed to work with a partly unpredictable production offer and consequently, current market practices are now to be revisited so that the renewable-based power systems of the future can be operated efficiently.

In this letter we place our focus on the merit order for generation dispatch. In particular, we show that, in a forward market with an increasing capacity from stochastic generating units, a merit order solely based on marginal costs does not guarantee increased market efficiency, but potentially the opposite. To regain market efficiency, the merit order for stochastic generation must also account for the *cost of its uncertainty*, defined as the expected cost of balancing its energy deviations during the real-time operation of the power system. In the next section we formulate a dispatch model that integrates this novel merit-order principle.

## II. Merit Order for Stochastic Producers

Consider an electricity market for short-term energy transactions that consists of a forward (typically day-ahead) market and a balancing market. The latter serves as an ex-post mechanism that clears the energy deviations with respect to the forward schedule.

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J. M. Morales, M. Zugno, and P. Pinson are with the Technical University of Denmark, Kgs. Lyngby, Denmark (e-mails: {jmmgo, mazu, ppin}@dtu.dk). S. Pineda is with the University of Copenhagen, Denmark (s.pineda@math.ku.dk).

We define the following model for energy dispatch in the forward market.

$$\underset{g,w,\delta^0,w^{\max};r_s,\delta_s,\forall s}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{D}}(g,w) + \mathbb{E}_S\left[\mathcal{C}^{\mathrm{B}}(r_s)\right] \tag{1a}$$

$$\text{s.t.} \quad f^{\mathrm{B}}\left(r_s,\delta_s,\delta^0\right) + W_s - w = 0\,, \ \ \forall s \in S\,, \tag{1b}$$

$$h^{\mathrm{B}}\left(r_s,\delta_s,g;W_s\right) \le 0\,, \ \ \forall s \in S\,, \tag{1c}$$

$$0 \le w^{\max} \le \overline{w}\,, \tag{1d}$$

$$\left(g,w,\delta^0\right) \in \arg\left\{ \underset{g',w',\delta^{0'}}{\text{Minimize}} \quad \mathcal{C}^{\mathrm{D}}(g',w') \right. \tag{1e}$$

$$\text{s.t.} \quad f^{\mathrm{D}}\left(g',w',\delta^{0'}\right) - d = 0\,, \tag{1f}$$

$$h^{\mathrm{D}}\left(g',\delta^{0'}\right) \le 0\,, \tag{1g}$$

$$\left. w' \le w^{\max} \right\}. \tag{1h}$$

Problem (1) is a stochastic bilevel program [2]. The lower-level problem (1e)–(1h) delivers the dispatch vectors $g$ and $w$ of conventional and stochastic producers, respectively, and the vector of voltage angles $\delta^0$ that minimize production costs in the forward market, $\mathcal{C}^{\mathrm{D}}(\cdot)$. Constraints (1f) enforces the nodal equilibria between offer and demand $d$, while constraints (1g) include generation and transmission capacity bounds. The dispatch of the stochastic generating units is limited through constraint (1h), where $w^{\max}$ is actually a decision variable controlled by the upper-level problem (1a)–(1d).

The upper-level problem (1a)–(1d) anticipates the balancing operation of the power system in a stochastic programming fashion. It provides the re-dispatch vector of flexible units $r_s$ and the vector of system-state variables $\delta_s$ for each considered scenario for stochastic production $W_s$, $s \in S$. Constraints (1b) ensure that flexible units are re-dispatched to accommodate the energy deviation of the stochastic generation from its forward schedule and constraints (1c) guarantee that transmission and generation capacity limits are still satisfied after re-dispatching. The upper-level objective function (1a), to be minimized, consists in the summation of the forward dispatch cost, $\mathcal{C}^{\mathrm{D}}(\cdot)$, and the expected cost of balancing, $\mathbb{E}_S\left[\mathcal{C}^{\mathrm{B}}(\cdot)\right]$. This way, by means of variable $w^{\max}$, the dispatch $w$ of stochastic generation is not only based on its marginal cost, if different from zero, but also on the cost of its uncertainty. Logically, variable $w^{\max}$ must be non-negative and lower than or equal to the stochastic production capacity $\overline{w}$, as expressed in (1d).

The stochastic bilevel program (1) can be solved using the same solution strategies as for price-based market-clearing problems [3].

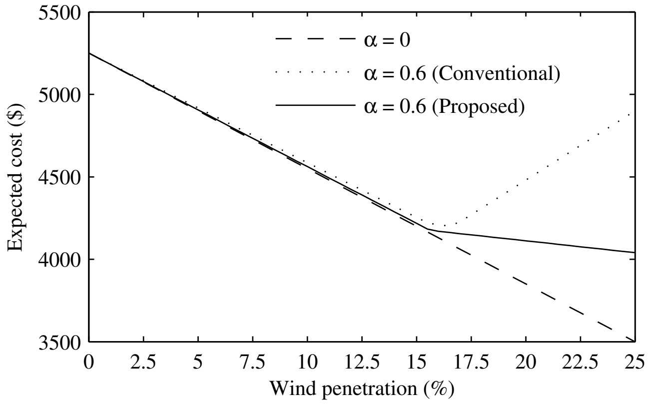


Fig. 1. Expected cost of the power system operation as a function of the amount of wind power production offered in the forward (day-ahead) market.

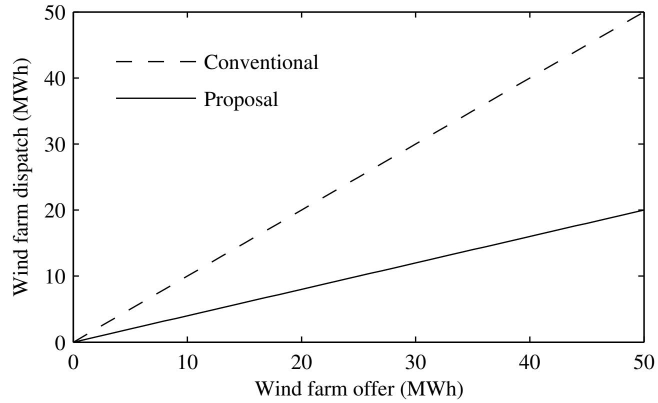


Fig. 2. Wind farm dispatch as a function of the amount of wind power production offered ($\overline{w} \cdot \hat{w}$) in the forward (day-ahead) market.

## III. Illustrative Example

Consider a power system consisting of three thermal units, G1, G2 and G3, with capacities 100, 100 and 50 MW, and marginal costs 35, 30 and $10/MWh, respectively. Besides, thermal unit G1 is willing to sell up to 20 MWh of additional energy for upward balancing at a price $40/MWh. Likewise this unit offers to repurchase up to 40 MWh for downward balancing at a maximum price of $34/MWh. Units G2 and G3 are, on the contrary, inflexible and as such, are not technically capable of providing balancing energy. The total system demand is 200 MWh, with a value of lost load equal to $200/MWh. For simplicity, but without loss of generality, we assume infinite transmission capacity. The power system also includes a wind farm, whose power output can be described by means of two equally likely scenarios of power values $\overline{w}(1-\alpha)\hat{w}$ and $\overline{w}(1+\alpha)\hat{w}$, where $\hat{w}$ is the predicted per-unit wind power production. We assume that the marginal cost of the wind power plant is zero and that its per-unit forecast error distribution is constant. Furthermore, following current market practices, the wind power producer offers its expected production ($\overline{w} \cdot \hat{w}$) in the forward (day-ahead) market.

Fig. 1 shows the expected total operating cost (i.e., the summation of forward costs and expected balancing costs) as a function of the wind power penetration level in the forward market, which is defined as the ratio of the predicted wind power output ($\overline{w} \cdot \hat{w}$) to the total system demand. Note that the expected total operating cost is an appropriate proxy of the long-term market efficiency as the generation dispatch problem is an operational (short-term) problem to be solved repeatedly over time. Fig. 1 includes three plots, each corresponding to a particular case, namely:

1) The wind power output is fully predictable ($\alpha = 0$, dashed line). Logically, in this ideal situation, an increase in the capacity of the wind farm leads to a decrease in the expected system operating costs.
2) The wind power output is uncertain and the wind farm is dispatched according to its marginal cost only ($\alpha = 0.6$, dotted line). In this case, an increase in the capacity of the wind farm may potentially reduce market efficiency due to a costly balancing operation, particularly for high levels of wind power penetration. Note that this case coincides with the way electricity markets are currently operated.
3) The wind power output is uncertain and the wind farm is scheduled based on model (1). This way, by means of a merit order for dispatching the wind farm that accounts for both its marginal cost and the expected cost of coping with its uncertainty, not only the expected system operating cost is reduced with respect to the previous case, but also higher capacity of stochastic production leads to higher market efficiency, as it happens for conventional generators that are dispatched according to their marginal cost.

Finally, Fig. 2 illustrates the dispatch of the wind farm as a function of its energy offer in the forward market (assumed to be equal to its mean power output, i.e. $\overline{w} \cdot \hat{w}$). Note that this offer is fully accepted if the merit order exclusively takes its zero marginal cost into consideration (dashed line). In contrast, such an offer is only partially accepted if the merit order for dispatch also considers the expected balancing costs (solid line), as the bilevel programming model (1) does.

## IV. Conclusion

In this letter, we show that the application to stochastic producers of the traditional merit order for dispatch based on marginal costs is cost-ineffective. Furthermore, we show that, in order to guarantee market efficiency under higher penetrations of stochastic capacity, the merit order should also account for the projected costs of balancing the forecast errors. We build a dispatch model that embeds such a criterion. Lastly, we use a small illustrative example as a proof of concept.

## References

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