Optimal Offering Strategies for Wind Power in Energy and Primary Reserve Markets

Tiago Soares, Pierre Pinson, Senior Member, IEEE, Tue V. Jensen, Hugo Morais, Member, IEEE

Abstract—In future power systems, wind power generation will play an important role in supplying electric power demand and even more in the design of future energy and reserve markets’ architecture. Consequently, it is likely that wind power plant operators will develop offering strategies in this competitive environment, accounting for the market rules and the operational capabilities of the turbines. We consider here two different offering strategies for joint participation in energy and primary reserve markets, based on the idea of proportional and constant splitting of potentially available power generation from the turbines. These strategies aim at maximizing expected revenue from both market floors based on probabilistic forecasts for quick reference. Other symbols are defined as required.

I. NOMENCLATURE

The main notation used throughout the paper is stated next for quick reference. Other symbols are defined as required.

A. Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>α</td>
<td>Proportional strategy split for energy and reserve</td>
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<tr>
<td>π</td>
<td>Prices and costs in the electricity market</td>
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<td>d</td>
<td>Energy imbalance</td>
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<td>h</td>
<td>Power imbalance</td>
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<tr>
<td>E</td>
<td>Energy</td>
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<td>P</td>
<td>Power (reserve)</td>
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<td>T</td>
<td>Total remuneration</td>
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<tr>
<td>R</td>
<td>Regulation energy market revenue</td>
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<tr>
<td>W</td>
<td>Potential penalty for primary reserve market</td>
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</table>

B. Indices

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>+</td>
<td>Positive imbalance (downward regulation)</td>
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<tr>
<td>−</td>
<td>Negative imbalance (upward regulation)</td>
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<tr>
<td>*</td>
<td>Available energy/power at real-time stage</td>
</tr>
<tr>
<td>bpt</td>
<td>Penalty cost for reserve imbalance</td>
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<td>c</td>
<td>Contracted energy/power at day-ahead stage</td>
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<td>cap</td>
<td>Reserve price at day-ahead stage</td>
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<tr>
<td>exp</td>
<td>Potentially available power generation at day-ahead stage</td>
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<td>Total observed power available eventually observed</td>
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<td>pt</td>
<td>Penalty for reserve imbalance</td>
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<td>F</td>
<td>Fixed reserve</td>
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<td>sp</td>
<td>Spot market</td>
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II. INTRODUCTION

The continuous deployment of wind power generation capacity in several countries, and especially in the Danish power system, makes it a potentially dominant energy source in view of its impact on power system operation and electricity markets. According to Energinet.dk (the Danish Transmission System Operator – TSO), December 2013 was an exceptional month where, on average, 54.8% of the electrical energy consumption was supplied by wind power [1]. According the same report, on December 1st, an extreme scenario with wind generation equal to 136% of the Danish power consumption was observed.

In the future, situations with very high wind (and most certainly also solar) generation will be more and more frequent, resulting in new challenges in power system operation [2]. The variability and limited predictability of wind power generation force the system operator to procure additional reserves to ensure adequate reliability of the electric power system [3]. However, according to [4], wind power plants are able to provide reserves themselves, thereby mitigating the additional procurement of reserves from other traditional resources. Thus, new mechanisms for reserve procurement, as well as for the participation of wind generation in providing reserves should be developed and implemented [5], [6]. Currently, wind turbine technology and wind farm control allow providing distinct ancillary services such as frequency and voltage control. Thus wind farms are able (i) to provide and control active power injection in a few seconds, (ii) to respond to reactive power demands in less than 1 second, (iii) to support and maintain voltage levels, and (iv) to provide kinetic energy (virtual inertia) [4], [7]–[9].

For optimal integration of wind power in energy and primary reserve markets, new business models and remuneration mechanisms should be thought of. The literature on optimal offering strategies for wind power producers in the day-ahead market while accounting for potential balancing costs has been flourishing over the last few years. This includes a number of studies on expected utility maximization strategies [10], additional consideration on risk-aversion and temporal dependencies [11], extension to LMP markets [12], appraisal of uncertainties on both wind and market quantities [13], as well as generalized opportunity cost bidding [14] among others.

In contrast, little attention has been paid to the joint offering under uncertainty of wind power generation in both energy and reserve markets. Such joint offering strategies are
expected to bring additional revenue streams to wind power plant operators. However, wind power plants face a big challenge which is to guarantee that power scheduled as primary reserve is available at any time without failure. The reserve market is designed to ensure the operation of electric power systems with appropriate levels of stability, safety, quality, reliability and competitiveness. In this way, intermittent energy resources, such as wind power, have difficulties to ensure and fulfil power scheduled to primary reserve.

A future reserve market must be designed to account for the possibility of wind failing to provide reserve, e.g. through penalties, if wind is to participate [15].

In that context, we formulate and analyse a number of joint offering strategies, as an extension of the classical expected utility maximization strategies proposed for the case of energy only, e.g. [10]. The aim is to maximize expected revenue from offering on both markets. These are based on two paradigms for the splitting of potentially available power generation into energy and reserve offers, which are referred to as proportional and constant strategies. Optimal offers are determined under uncertainty based on probabilistic forecasts of potential power generation for the market time unit considered. Additional input variables include expected market prices (for energy and reserve) as well as expected penalties on balancing and reserve mechanisms. The methodology is applied and demonstrated on numerical examples.

The paper is structured as follows. Section III describes electricity markets characteristics with a perspective on future energy and reserve market trends. Section IV presents the detailed formulation of joint offering strategies (for proportional and constant strategies) in energy and primary reserve markets. Section V describes our empirical investigation based on a set of numerical examples. Section VI assembles the most important conclusions and discussion.

III. WIND POWER IN ELECTRICITY MARKETS

A. Day-ahead market

The continuous penetration of wind power generation in electric power systems has been changing wholesale market characteristics. In fact, wind power generation has been electric power systems has been changing wholesale market reserve. Difficulties to ensure and fulfil power scheduled to primary reserve, such as wind power, have difficulties to ensure and fulfil power scheduled to primary reserve.

The first is the regulation market. In this market, the system operator purchases the required regulating power to balance the system (primary frequency control). The participants in the market offer to buy or sell regulating power, a priori to the energy delivery. For instance, wind generators use this mechanism to mitigate its forecast errors. Wind participants with positive imbalance (energy surplus) can mitigate wind participants with negative imbalance (energy deficit).

The second stage is called the balancing market. This stage is used to mitigate the remaining deviations on the power system. At this stage, the system operator allocates costs to market participants that cause system imbalance. For instance, wind power participants that do not correct their deviations, can be harshly penalised. Moreover, the system operator buys all the necessary power to balance the system, the cost being allocated to market participants.

In the balancing market as a whole there are three possible situations: (i) positive balance when supply is higher than the demand, so there is a need for downward regulation; (ii) negative imbalance when supply is lower than demand, so there is a need for upward regulation; and (iii) no imbalance, when supply matches the demand.

Similarly, market sellers (such as wind power plants) have three possible situations: (i) positive imbalance when actual generation is higher than scheduled generation; (ii) negative imbalance when actual generation lower than scheduled generation; and (iii) no imbalance when actual generation match the scheduled generation in the market.

For each of the combined situations balancing prices are obtained. These are usually hard to predict resulting in high variation. NordPool uses a two-price mechanism to settle the cost for the imbalance. The two-price mechanism penalize the market participants (wind power participants) that contribute to the overall system imbalance, while remunerate the wind power participants that help to balance the system at day-ahead clearing price for the operation period.

B. Balancing market

The balancing market is used to compensate for energy deviations in real time from the day-ahead and intraday exchange. In the Nordic countries, the balancing market is managed by the TSO. This market is performed during the operating hour and is usually split in two different stages [18]. The first is the regulation market. In this market, the system operator purchases the required regulating power to balance the system (primary frequency control). The participants in the market offer to buy or sell regulating power, a priori to the energy delivery. For instance, wind generators use this mechanism to mitigate its forecast errors. Wind participants with positive imbalance (energy surplus) can mitigate wind participants with negative imbalance (energy deficit).

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C. Offering strategies on day-ahead and balancing markets

Trading energy on day-ahead and balancing market is a well-known problem for wind power participants in electricity markets. Several works have been developed for this purpose with different strategic offering approaches to the uncertainty in production and in market prices. One of the approaches is to determine the optimal day-ahead market bid for a wind power participant considering a certain quantile of the distribution of wind power generation. This approach is based on a dynamic function (optimal quantile) considering the day-ahead and balancing prices [10], [12], [13].

D. Joint offering on energy and primary reserve market

Currently and even more in the future, wind power plants will be able to provide some type of ancillary services, such as
frequency and voltage control [4]. Nowadays, wind power plants are willing to participate in energy and primary reserve market. However, there is a need for developing offering strategies for energy and primary reserve markets that can meet an improvement on the economic benefit that wind power participants may get from the market.

In the present work, the quantile strategy (proposed in [10]) is adapted to consider the participation of wind power plants on energy and primary reserve market. The main goal is to provide a strategic offering approach that can optimally determine the bid of wind power to submit in energy and primary reserve market.

The offering strategy takes into account different characteristics of both markets. On one hand, the wind energy bids that should be submitted in day-ahead market, considers the imbalance situations that may occur in the balancing market. On the other hand, bids submitted in the primary reserve market takes into account the possibility of wind power fail to provide the service. Thus, the power system imbalance is higher as well as decreases the proper levels of power system safety and reliability. Moreover, a high penalty for wind power plants to fail providing primary reserve should be considered. Thus, optimal offering strategy for energy and primary reserve market can be obtained.

IV. METHODOLOGY

In this section, the proposed methodology to optimize the offering strategy of wind power producers in energy and primary reserve market is described. Time indices are not used, since all variables and parameters are for the same market time unit. The objective function is optimized with the aim of finding the maximum expected revenue that wind power plants could obtain from participation in both energy and primary reserve markets. The revenue $R$ of a wind power plant for a given market time unit can be formulated as

$$ R = \pi^p E^c + \pi^{cp} P^c + T^c - W^c $$

where $\pi^p$ is the spot price, $E^c$ is the amount of energy sold in the day-ahead electricity market, $\pi^{cp}$ is the capacity price for primary reserve allocation, $P^c$ is the proposed level of primary reserve capacity offered at that same time, $T^c$ is the revenue from the regulation market (most likely penalizing) and $W^c$ is the potential penalty cost of wind power plant failing to provide the scheduled primary reserve. The future and simultaneous participation of wind power plants on energy and primary reserve market should be based on offering strategies with strategic behavior, i.e., accounting for forecast uncertainty and potential recourse actions. In the present case, we assume that the splitting between energy and reserve is fixed at the day-ahead stage, and not modified in real-time. Considering such recourse actions would comprise natural extensions of the proposal strategies we describe in the following.

A. Proportional wind offering strategy

The proportional wind offering strategy (illustrated in Fig. 1) consists in a proportional curtailment of potentially available power generation to yield an energy offer $E^c$ and a primary reserve offer $P^c$ [19], where

$$ E^c = \alpha^c E^{exp} $$
$$ P^c = (1 - \alpha^c)E^{exp} $$

In the above, $E^{exp}$ denotes the potentially available power generation for that market time unit and $\alpha^c$ is the strategy parameter controlling the proportional split between energy and primary reserve bids. This last parameter naturally varies between 0 (for full reserve allocation) and 1 (for full energy allocation).

![Fig. 1. Proportional wind offering strategy (reproduced with authorization from [15], [19]).](image)

On the other hand, the eventually observed wind power production $E^{obs}$ is similarly composed by an energy portion $E^*$ and $P^*$ the amount of primary reserve actually available, i.e.

$$ E^* = \alpha^* E^{obs} $$
$$ P^* = (1 - \alpha^*)E^{obs} $$

where $\alpha^*$ is the strategy parameter used when reaching real-time operation, considering as a recourse variable or not. Energy $d^*$ and power $h^*$ imbalances are defined as

$$ d^* = E^* - E^c $$
$$ h^* = P^* - P^c $$

Assuming that wind power plants could fail to provide primary reserve, a penalty cost is considered as an incentive for wind power plants not to fail. It is defined as

$$ W^c = \begin{cases} \pi^{d^*} h^*, & h^* \geq 0 \\ \pi^{h^*} h^*, & h^* < 0 \end{cases} $$

where $\pi^{d^*} = 0$ since (extra) positive reserve imbalance is not detrimental to the system’s reliability, while $\pi^{h^*}$ is the penalty for negative reserve imbalance. The regulation market revenues are positive if $d^* \geq 0$ (energy surplus) and negative if $d^* < 0$ (energy deficit),

$$ T^c = \begin{cases} \pi^{d^*} d^*, & d^* \geq 0 \\ \pi^{h^*} d^*, & d^* < 0 \end{cases} $$

Where $\pi^{d^*}$ is the unit down-regulation price, which is received by the power plant for being long, while $\pi^{h^*}$ is the up-regulation price that is paid by the power plant for being short. Imbalance prices necessarily depend on the rules of the market considered. Different markets have different regulation mechanisms. In some markets regulation prices are merely defined as a portion of the market clearing price. However, some markets define a more complex relationship between
regulation and spot prices. For instance in the NordPool, regulation prices depend not only of the spot price but also on the sign of the system imbalance [10]. Assuming the NordPool balancing mechanisms, the prices are restricted taking into account the system needs. In cases where the system imbalance is negative (energy surplus − need of downward regulation), the prices are denoted as

\[ \pi^{e^+} \leq \pi^w \]

\[ \pi^{e^-} = \pi^w \]  

(7)

On contrary, when system imbalance is positive (energy deficit − need of upward regulation), the prices holds that

\[ \pi^{e^+} = \pi^w \]

\[ \pi^{e^-} \geq \pi^w \]  

(8)

while during hours of perfect balance the down-regulation price \( \pi^{e^+} \) and up-regulation price \( \pi^{e^-} \) are equal to the spot price \( \pi^w \). In this context, it is possible to determine the revenue \( R \) using

\[ R = \pi^w E^p + \pi^{bpt} P^p - T^r - W^r \]  

(9)

instead of (1), such that the revenue for wind power plant is determined based on the combination of the income from selling of realized wind generation at the spot price and the capacity payment for wind availability to provide primary reserve, less the regulation and penalties costs. In (9), the regulation costs are defined as

\[ T^r = \begin{cases} \pi^{e^+} d^e, & d^e \geq 0 \\ -\pi^{e^-} d^e, & d^e < 0 \end{cases} \]

(10)

The variables \( \pi^{e^+} \) and \( \pi^{e^-} \) are the regulation unit costs for positive and negative wind producer imbalances, given by

\[ \pi^{e^+} = \pi^w - \pi^{bpt} \]

\[ \pi^{e^-} = \pi^w - \pi^{bpt} \]

(11)

On the other hand, the penalty costs depends on the reserve imbalance which can be positive or negative, such that

\[ W^r = \begin{cases} \pi^{bpt^+} h^+, & h^+ \geq 0 \\ -\pi^{bpt^-} h^-, & h^- < 0 \end{cases} \]

(12)

where \( \pi^{bpt^+} \) is the loss opportunity penalty cost for positive reserve imbalance which is not harmful to the system, and \( \pi^{bpt^-} \) is the unit penalty cost for negative reserve imbalance, given by

\[ \pi^{bpt^+} = \pi^{bpt} - \pi^{bpt^+} \]

\[ \pi^{bpt^-} = \pi^{bpt} - \pi^{bpt^-} \]

(13)

Assuming that wind power plant is a price-taker, the maximization of its expected revenues leads to the minimization of the expectation of regulation and penalties costs, where the optimal values for the offering parameters are the solution of

\[ (\tilde{\alpha}^e, \tilde{\alpha}^c) = \arg\min_{\alpha^e, \alpha^c} \mathbb{E}\{T^r + W^r - \pi^w E^r - \pi^{bpt} P^p\} \]  

(14)

The problem presented in equation (14) is an extended version of loss function used in [10], where the available wind power is split into two different market products that are energy and primary reserve.

The share of the available expected power \( \alpha^c \) and observed power \( \alpha^c \) for energy and reserve participation is assumed to be the same \( (\alpha^e = \alpha^c) \), though this assumption could be relaxed in future work. The interest of not considering recourse actions is that one may obtain closed-form solution to the optimal offering problem such as that given by (14).

Consequently, the total expected costs \( \tilde{\alpha}^e \) are given by

\[ \tilde{\alpha}^e (E^p, \alpha^c) = \int_0^{E^p} \left[ \pi^{bpt} \left( 1 - \alpha^e \right) \left( E^p - x \right) \right] f(x) dx + \int_0^{\alpha^c} \left[ \pi^{e^+} \alpha^c \left( x - E^p \right) - \pi^{bpt} \left( 1 - \alpha^c \right) \right] f(x) dx \]

(15)

where \( f(x) \) is the probability density function of the wind power plant, given by a probabilistic wind power forecast available at the time of offering. The derivative of (15) with respect to \( E^p \) considering the Leibniz rule for derivation under the integral sign is given by

\[ \frac{\partial \tilde{\alpha}^e}{\partial E^p} (E^p, \alpha^c) = \int_0^{E^p} \left[ \pi^{bpt} \left( 1 - \alpha^e \right) \left( E^p - x \right) \right] f(x) dx + \int_0^{\alpha^c} \left[ \pi^{e^+} \alpha^c \left( x - E^p \right) - \pi^{bpt} \left( 1 - \alpha^c \right) \right] f(x) dx \]

(16)

where \( F \) is the cumulative distribution function of the wind power probabilistic forecast used as a basis for decision-making. Therefore, the potentially available power to offer overall (i.e., for energy and reserve) is a quantile of the wind power distribution.

On the other hand, the derivative of (15) with respect to \( \alpha^c \) is as follows

\[ \frac{\partial \tilde{\alpha}^e}{\partial \alpha^c} (E^p, \alpha^c) = \int_0^{E^p} \left[ \pi^{bpt} \left( 1 - \alpha^e \right) \left( E^p - x \right) \right] f(x) dx + \int_0^{\alpha^c} \left[ \pi^{e^+} \alpha^c \left( x - E^p \right) - \pi^{bpt} \left( 1 - \alpha^c \right) \right] f(x) dx \]

(18)

Equation (18) is a nonlinear equation in \( E^p \) which doesn’t depend on \( \alpha^c \), and \( E^p \) is thus determined from the prices above. Observing that, equation (15) is a linear function of \( \alpha^c \) with the sign of the linear coefficient depending only on \( E^p \), the minimum cost must occur for \( \alpha^c = 0 \) or \( \alpha^c = 1 \). Thus, the energy bid corresponds to full expected energy when reserve penalties higher than energy penalties. On the contrary, penalties for energy higher than reserve, results in total expected power being submitted in the primary reserve market.

B. Constant wind offering strategy

The constant wind offering strategy (Fig. 2) is based on a constant curtailment of power over a certain expected level of wind power [19], where

\[ E^e = E^p - P^r \]

\[ P^r = P^a \]  

(19)
$P^R$ is the amount of fixed reserve to be submitted as primary reserve in the reserve market, and $X\%$ is the percentage of installed wind power.

This problem has three different regions of operation (Fig. 3): when observed wind energy is lower than fixed reserve; observed wind power between fixed reserve and expected wind power; and observed power higher than expected wind power.

The mathematical formulation that leads to the minimization of the total expected costs ($\hat{O}$) is as follows

$$\hat{O}(E^{\exp}, P^*) = \int_0^{E^{\exp}} \left[ \pi^{pr} - (E^{\exp} - p^*) - \pi^{pr} (E^{\exp} - x) \right] f(x) dx$$

$$+ \int_{E^{\exp}}^{P^*} \left[ \pi^{pr} - \pi^{sp} (E^{\exp} - x) - \pi^{sp} (x - P^*) \right] f(x) dx$$

$$+ \int_{P^*}^{\infty} \left[ \pi^{sp} (x - P^*) - \pi^{sp} P^r \right] f(x) dx$$

(22)

The integrals correspond respectively to the situations 1, 2, and 3 in Fig. 3. We proceed to minimize this function by differentiation. The derivative of (22) with respect to $E^{\exp}$ is given by

$$\frac{\partial \hat{O}}{\partial E^{\exp}}(E^{\exp}, P^*) = \int_0^{E^{\exp}} \pi^{pr} f(x) dx + \int_{E^{\exp}}^{P^*} \pi^{pr} f(x) dx + \int_{P^*}^{\infty} \pi^{sp} f(x) dx$$

(23)

which yields

$$E^{\exp} = F^{-1} \left[ \frac{\pi^{pr}}{\pi^{pr} + \pi^{sp}} \right]$$

(24)

On the other hand, the derivative of (22) with respect to $P^*$ taking into account the Leibniz rule for derivation under the integral sign is as follows

$$\frac{\partial \hat{O}}{\partial P^*}(E^{\exp}, P^*) = \int_0^{E^{\exp}} \left[ \pi^{pr} - \pi^{sp} (E^{\exp} - x) \right] f(x) dx$$

$$+ \int_{E^{\exp}}^{P^*} \left[ \pi^{sp} - \pi^{sp} (x - P^*) \right] f(x) dx$$

$$+ \int_{P^*}^{\infty} \left[ \pi^{sp} (x - P^*) - \pi^{sp} P^r \right] f(x) dx$$

(25)

which yields

$$F(P^*) = \frac{\pi^{sp} - \pi^{sp}}{\pi^{pr} - \pi^{pr} + \pi^{sp} - \pi^w}$$

(26)

1) Normal operation

The following formulation is valid for cases where $\pi^{pr} \geq \pi^{sp}$ and $\pi^{sp} \geq \pi^w$. These assumptions are realistic; it is much more harmful to the system if wind power producer fail to provide reserve than energy. Thus, reserve penalty is higher than energy penalty. In the same context, make sense that the capacity price for reserve is higher than the spot price, in order to assure proper levels of reserve.

Assuming wind power plant is a price-taker, the expected available power $E^{\exp}$, and the reserve variable $P^R$, are the variables related to the expectation of regulation and penalties cost. The minimization of the expected costs is given by

$$(\hat{E}^{\exp}, \hat{P}^R) = \arg \min_{E^{\exp}, P^R} \mathbb{E} \left\{ T^* + W^* - \pi^{sp} E^{\exp} - \pi^{sp} P^* \right\}$$

(21)

2) Special operation – reserve only market

There are a few cases where the strategy should be decoupled to participate in a single reserve market: when the energy bid is negative – only reserve market participation; and when $\pi^{pr} \leq \pi^{sp}$ and $\pi^{sp} \geq \pi^w$, the full availability of the wind producer should be submitted to the reserve market.

For that cases of single participation in the reserve market, the objective function is a special case of equation (22) and is as follows

$$\hat{O}(P^*) = \int_0^{E^{\exp}} \left[ \pi^{pr} - (P^* - x) - \pi^{sp} x \right] f(x) dx$$

$$+ \int_{E^{\exp}}^{P^*} \left[ \pi^{sp} (x - P^*) - \pi^{sp} P^r \right] f(x) dx$$

(27)

Following the derivative with respect to $P^R$ using the
Leibniz rule for derivation under the integral sign, one can obtain
\[
\frac{\partial \bar{O}}{\partial \bar{P}(P^*)} = \int_{0}^{\bar{P}} \bar{\pi}^\pi f(x) dx + \int_{\bar{P}}^1 \left[ \bar{\pi}^\pi - \bar{\pi}^\pi \right] f(x) dx
\]
resulting in the quantile for energy participation,
\[
P^\pi = F^{-1} \left( \frac{\bar{\pi}^\pi + \bar{\pi}^\pi - \bar{\pi}^\pi}{\pi^{\pi^\pi} + \bar{\pi}^\pi + \bar{\pi}^\pi - \bar{\pi}^\pi} \right)
\]

3) Special operation – energy only market

In cases where \( \pi^{\pi^\pi} \geq \pi^\pi \) and \( \pi^{\pi^\pi} < \pi^\pi \), it is intuitive that wind power producer will opt to participate only in the energy market. Thus, the total expected availability of the wind power producer takes into account just the terms related to the energy market. The objective function for this case is a particular case of equation (22), given by
\[
\bar{O} \left( E^{\pi^\pi} \right) = \int_{0}^{E^{\pi^\pi}} \pi^\pi \left( E^{\pi^\pi} - x \right) - \pi^\pi x \right] f(x) dx + \int_{E^{\pi^\pi}}^1 \left[ \pi^\pi - \pi^\pi \right] f(x) dx
\]
The derivative of (30) with respect to \( E^{\pi^\pi} \) taking into account the Leibniz rule becomes
\[
\frac{\partial \bar{O}}{\partial E^{\pi^\pi}} = \int_{0}^{E^{\pi^\pi}} \pi^\pi f(x) dx + \int_{E^{\pi^\pi}}^1 \pi^\pi f(x) dx
\]
which results in the quantile for energy participation
\[
P^\pi = F^{-1} \left( \frac{\pi^\pi}{\pi^\pi + \pi^\pi} \right)
\]

V. EVALUATION OF OFFERING STRATEGY

An empirical investigation for the evaluation of the offering strategies for wind power participation in energy and primary reserve market is performed in this section.

A. Test cases

1) Base case

The base case comprises the following assumptions. For participation in the energy market is assumed: a spot market price (\( \pi^\pi = 22 \) €/MWh); a unit down-regulation price (\( \pi^\pi = 17 \) €/MWh), which is paid by the power plant for being long; and a unit up-regulation price (\( \pi^\pi = 32 \) €/MWh), which is paid by the power plant for being short. For participation in primary reserve market is assumed: a capacity price (\( \pi^{\pi^\pi} = 25 \) €/MW); a neutral primary reserve penalty for positive reserve imbalance (\( \pi^{\pi^\pi} = 0 \)); and a penalty for negative reserve imbalance (\( \pi^{\pi^\pi} = 60 \) €/MW). An installed capacity of 30 MW for the wind power plant is assumed. Furthermore, the wind power plant production is modeled based on a beta distribution with shape parameters \( a=2 \) and \( b=4 \). The expected remuneration is evaluated using 1000 samples for wind production drawn from this beta distribution.

The evaluation of the proportional strategy is performed by an iterative process. \( \alpha^c \) is assumed to vary between 0 and 1 with step of 0.03. \( E^{\pi^\pi} \) is determined based on equation (17) for each \( \alpha^c \). Then the total remuneration for each given \( \alpha^c \) is determined.

The constant strategy is evaluated using the realistic assumption of the relation between penalties and market prices, such that \( \pi^{\pi^\pi} \geq \pi^\pi \) and \( \pi^{\pi^\pi} \geq \pi^{\pi^\pi} \). In this case, equations (24) and (26) are used to determine the expected power and the reserve bid, respectively.

Table I shows a comparison between three different strategies for participation in electricity markets (proportional, constant, and energy-only). The energy-only strategy is based on the common newsvendor problem [10]. Thus, the quantile for this strategy is given by equation (32).

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Proportional</th>
<th>Constant</th>
<th>Energy-only</th>
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<tbody>
<tr>
<td>Energy bid (MWh)</td>
<td>7.0181</td>
<td>3.5162</td>
<td>7.0181</td>
</tr>
<tr>
<td>Reserve bid (MW)</td>
<td>0</td>
<td>3.5018</td>
<td>-</td>
</tr>
<tr>
<td>Total expected power (MW)</td>
<td>7.0181</td>
<td>7.0181</td>
<td>7.0181</td>
</tr>
<tr>
<td>Expected inflow (€)</td>
<td>225.48</td>
<td>235.61</td>
<td>225.48</td>
</tr>
<tr>
<td>Expected costs (€)</td>
<td>29.92</td>
<td>33.03</td>
<td>29.92</td>
</tr>
<tr>
<td>Expected remuneration (€)</td>
<td>195.56</td>
<td>202.58</td>
<td>195.56</td>
</tr>
</tbody>
</table>

Furthermore, Table I provide the behavior of each offering strategy for market participation, as well as the respective expected remuneration. One can verify that constant strategy has higher economic expected return than the other strategies.

2) Full reserve case

Assuming that \( \pi^{\pi^\pi} \) is much higher than \( \pi^\pi \), for instance \( \pi^{\pi^\pi} = 40 \) €/MW, the strategies may split differently the energy and reserve bids. Table II compare the strategies participation in both energy and primary reserve market, including the expected remuneration that the wind power producer can obtain in that condition.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Proportional</th>
<th>Constant</th>
<th>Energy-only</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy bid (MWh)</td>
<td>12.0631</td>
<td>9.9361</td>
<td>7.0181</td>
</tr>
<tr>
<td>Reserve bid (MW)</td>
<td>0</td>
<td>9.9361</td>
<td>7.0181</td>
</tr>
<tr>
<td>Total expected power (MW)</td>
<td>12.0631</td>
<td>9.9361</td>
<td>7.0181</td>
</tr>
<tr>
<td>Expected inflow (€)</td>
<td>381.57</td>
<td>365.24</td>
<td>225.48</td>
</tr>
<tr>
<td>Expected costs (€)</td>
<td>75.72</td>
<td>55.86</td>
<td>29.92</td>
</tr>
<tr>
<td>Expected remuneration (€)</td>
<td>305.85</td>
<td>309.40</td>
<td>195.56</td>
</tr>
</tbody>
</table>

One can verify that there is a change on the behavior of both proposed strategies. Both strategies allocate all the available energy to primary reserve market. This is due to the fact that the revenue from primary reserve market is much higher than the revenue from energy market. In this case, both proposed strategies get better results than the energy-only strategy.

B. Constant strategy behavior

1) Objective function behavior

The objective function for the base case is illustrated in Fig. 4. One can verify that the formulation is convex and always converge to optimal solution. The aim of the formulation is to minimize the expected costs, which leads to the maximization
of the expected return.

The expected reserve bid can never be higher than the total expected energy, hence the triangular cutoff for higher expected reserve.

2) Constant strategy performance under different spot and primary reserve market prices

The behavior of the constant strategy strongly depends on the difference between the spot and primary reserve market prices. Fig. 5 depicts the behavior of the strategy under different spot and reserve market prices. The simulation is performed under the base case data with variation in spot and primary reserve prices. The spot prices varies between 17 and 32 €/MWh, while the primary reserve market price is represented by three cases, 25, 35 and 50 €/MW, respectively.

The simulation shows that increasing primary reserve price leads to higher remuneration, as expected. However, at a certain point, the reserve market no longer generate higher profit than the energy market, thereby the full availability is submitted to the energy market. This occur when the spot price is higher than 25 €/MWh. In case 1 (reserve price of 25 €/MW) this occurs because the primary reserve penalty is higher than the energy penalty, so there is no incentive to participate in the primary reserve market.

The intersection between energy and reserve curve for case 1, gives precisely the result of the base case for the constant strategy.

VI. CONCLUSIONS

The increasing flexibility of wind power plants, combined with the willingness of system and market operators to review grid codes and market mechanisms, will lead to a further integration of wind power in power systems. Wind power plants may certainly then end up providing more market services, such as primary reserve. For that purpose, wind power plants will eventually develop offering strategies for participation in both energy and primary reserve markets.

The main motivation behind this work was to formulate and derive optimal offering strategies for this case of wind power plants participation in energy and primary reserve markets. Two strategies based on existing operational proposals for reserve provision were considered, i.e., proportional and constant reserve offering strategies. These strategies yield different behavior and flexibility to increase wind power owners expected profits. Optimal offering is ensured in each strategy by maximization of the expected revenue from both trading floors.

First and foremost, the simulation results show that such strategies are able to provide additional profits, in expectation. On the one hand, the proportional strategy leads to a binary behavior where all the available energy is submitted in either energy or reserve market. Consequently, under current market design, it would hence be unlikely that wind power plants would end up offering primary reserve. On the other hand, the
constant strategy enables a joint participation of wind power plants in both energy and primary reserve markets. This strategy exhibits a more balanced offering behavior, where in most cases there is always participation in both markets. However, the use of our formulation is conditioned by our initial assumptions. It is indeed assumed that the reserve penalty is higher than the energy penalty, and the reserve price is higher than the spot price, which is intuitively expected in practice. In cases of different assumptions, the entire availability will be submitted to one of the markets, as for the proportional strategy.

Besides the main message, this work has allowed to reach a number of practical conclusions. The most important are that: (i) the results from application of these offering strategies strongly depend on the market prices and penalties for energy and reserve; (ii) the proportional strategy is readily converging to the market that presents greater profitability; (iii) the constant strategy makes wind power generation offer both energy in reserves under adequate market conditions; and (iv) proportional and constant strategy ensures higher profit than the energy-only market strategy.

Future work will focus on the improvements of the strategies considering that the share for energy and reserve submitted in the day-ahead market can change in the balancing market. For that purpose, stochastic programming may be used, considering the share between energy and reserve (α) as a recourse variable. Such work can integrate test cases for wind farms in the Danish power system under Nord Pool electricity market rules. Finally, proposals for market design improvements will be made, in order to yield an optimal participation of wind power in both energy and ancillary service markets in the future.

VII. ACKNOWLEDGMENT

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VIII. REFERENCES


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