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Combinatorial price offer for a wind turbine with flexible load considering the uncertainty to increase the benefit of wind turbine

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Highlights

- Integrated bidding strategy for wind turbine and demand response to increase both benefits
- Improvement of prediction results for power market and wind speed variables by applying the new fuzzy-based model
- Considering uncertainty in optimal bidding model in market price and wind speed
- Demand response modeling as exponential model
- Optimal bidding results in achievement by applying mathematics optimal model

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Abstract

Wind energy is one of the most important renewable energies in the present and future. However, one of the significant challenges is offering the amount of generation and generation price in the next-day market because, on the one hand, this energy has nonlinear behavior, and on the other hand, any imbalance between forecast and generation results in the generation unit being fined. In this paper, a method is presented to propose wind turbine generation by increasing the forecast accuracy and combination with flexible load and uncertainties. This increases the revenue of the wind generator companies and consumers and guarantees the connection of wind generators. In fact, in this paper, the agreed price between the wind and load is flexible so that this agreed performance will be beneficial to both wind generation and the elastic load. In this modeling, first, the system equations in the market are written and merged. To increase the revenue, the uncertainties are considered, and it is shown that their effect can change the gain in wind turbine and load. The price and wind prediction will be conducted using one of the previous methods, and the primary purpose here is to increase the system revenue. To sum up, this paper introduces the integrated offering strategy model for wind turbines, and demand response to the support of wind turbines in the power market is proposed. The aim of this strategy is to increase renewable generations and demands profits in the day-ahead market. In this paper, the suggestions include the integrated offering of power, uncertainties modeling, using the neural-fuzzy model for predictions, flexible loads, etc. are proposed to achieve the optimal profits. Modeling is done using the MATLAB application to calculate Spain's wind and price information in Spain, and the performance output results are demonstrated thoroughly.

1. Introduction

1.1. Motivation

Wind energy is one of the renewable energy resources, which has grown significantly over the recent decades in different countries. For instance, wind energy makes up 15% of the power grid in Spain. The worldwide installed capacity of wind turbines at the end of 2010 was approximately 430 TW-hours, which is 5.2% of global demand. With the current increment rate, the worldwide energy union estimates that by the end of 2015, the overall installed capacity can be as much as 600 GW. Also, by ending the end of 2020, it will be as much as 1500 GW, 12% of total global demand [1-2].

On the other hand, after changing the electricity trade system in 1980, a new electricity trade system was presented using Non-exclusive methods and based on government policies. It is considered a product with market

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laws and revenues. This approach for trading electrical energy is very fair, and it leads to optimum prices in the market [3]. This exchange is carried out at almost every point in buying and selling in the next-day market (the deals are made one day before generation and consumption). The generation companies and buyers offer the amount of generated and consumed power [4]. However, for the highly uncertain wind nature, usually, the shorter the prediction period, the higher the accuracy [5]. Hence, forecasting the wind turbine generator for the next day's market will be very difficult [6]. Predicting the market price and generation amount are two significant challenges for wind generation companies participating in the next-day market. These two challenges include uncertainties, where the next day's market price prediction has fewer problems than the wind generation prediction.

Based on the market laws, the wind turbine should report the amount of generation for the next day's market every hour of the day without certainty. This uncertainty imbalanced the wind turbine's actual generation and the predicted value on the given sale day. Should trade this imbalance in the instantaneous market. The wind turbine's high cost will be imposed since other generation companies' generation increases and decreases in this market [7]. Hence, the generation proposal strategy for the wind turbine is one of the most fundamental challenges for generation companies.

1.2. Literature review

Numerous solutions are presented for the participation of wind turbine generation in the power market [8]. Most of these solutions should estimate the wind power first, and then the generation for the next hours can be proposed to the system. Using some of the solutions, the estimation accuracy is increased [9, 10]. However, the accuracy only increases when the prediction is conducted in a shorter period [11]. Next-day market update in the mid-day market method is proposed to decrease the imbalance and improve prediction accuracy [12]. In [13], the amount of generated power of renewable energies that face uncertainty is considered as adjustment power of the market to encourage the generation companies. In addition, reference [14] has discussed how renewable energies participate as retailers.

Estimation of imbalance price can be advantageous for generation companies with high uncertainty. Considering this imbalance of price in power amount proposal on the next day can improve the bid [15]. Optimum recommendation of power strategy, due to uncertainty in market prices and generated power, is another method to decrease the losses imposed by imbalance [16]. To reduce the losses due to inequality, references [17] and [18] have discussed combining the proposal for wind generation and hydroelectric generator companies. However, in general, it can be said that wind estimation methods for the next-day market are always mistaken. This prediction accuracy can decrease the wind turbine problem to some extent. Other forms have sound effects in increasing the revenue of wind generator companies but cannot guarantee the optimal condition.

In [19], a VPP containing WT, PV panels, energy storage, and demand response are considered for an integrated offering strategy in the power market. In this method, the uncertainties are considered for market and production variables. Also, utility function is applied for modeling of demand response. The robustness optimization model is proposed in [20] to achieve the best quality electric power from renewable energy besides maximizing the profit of these productions by considering FACTS devices. In this model, the optimal placement is applied for FACTS devices in the power system to the best corporations of renewable energies. The communication model based on microgrids is considered for modeling in the power market [21]. In order to control the power amount of generations, the generators are controlled by multi-layer controllers in this model. Risk-based stochastic optimization, short-term scheduling, linearized AC power follow considering, demand response, and storage modeling are the main of contributions of this technique. The four-technology model has been studied for the growth of wind turbines in [22]. The case studies of this paper are related to China and Germany countries. The management of multi-wind turbines is the main contribution of this study.

1.3. Contributions

In this paper, a proper method is proposed to integrate the wind generator and flexible loads to increase the revenue of the both sides. In addition to increasing the income of both sides, uncertainties of the next-day market and generated power of wind turbines are considered, and probable optimizations are suggested to propose the price in the next-day market. Generation Uncertainty and the offered prices of wind turbines and load combinations are considered, which can increase the revenue of both of them. Also, a robust neural-fuzzy method is used to predict the wind power, next day market price, and uncertainty, which can increase the prediction accuracy and decrease the financial losses. Finally, the modeling is conducted in MATLAB application, and the results in different scenarios are presented to compare and analyze the efficiency of the proposed method. In sum up, the main contributions of this paper as follow;

- ✓ Considering a new model for integrated bidding strategy for the day-ahead market to reduce the economic loss of wind turbines
- ✓ Increase the profit of renewable power generations beside demands in the power market
- ✓ Modeling the integrated structure for wind turbines and demand response
- ✓ Considering uncertainties for power market price and wind speed to overcome the economic loss of uncertain natures
- ✓ Applying the new Fuzzy based model to achieve optimal bidding power to the prediction of day-ahead market price and wind speed

1.4. Paper organization

This paper contains six sections; the market model and various market considerations are described in the next section. In the third section, the study system and its modeling are presented. The market pricing model, wind turbine, and demand response model are the main subsection of section 4. Results and discussion of the paper are described in section 5, which is shown the performance of the proposed strategy. Finally, the sixth section contains the paper's conclusion.

2. Market Model

In the proposed method, different markets are considered for a wind turbine. These wind turbines should present their offer to the market as follows.

2.1. Next day market

First, the wind turbines should offer their amount of generated power based on the conducted prediction for the next day's market. However, the number of uncertainties for wind generation companies is higher than for other generation companies. Wind generation companies should estimate the price for the next-day market and offer based on their own losses and revenues. However, the critical matter is that the wind generation companies are not informed about their generation in the next day. Wind fluctuation is far higher than anything else, and its prediction for one day through any method has many errors. Hence, it is not fair to base the losses and revenue on these offers.

2.2. Instantaneous market

To compensate the imbalance faults, flexible loads along with wind generation companies can be used. These loads can increase their consumption when the generation energy by the wind turbine is higher than the predicted value and decrease their consumption when the generation is lower than the prediction. In addition, when the price in the instantaneous market is high, these loads reduce their consumption to sell the generated wind energy can be sold to the grid. Also, when the market price is low, the shortage in load consumption is compensated through the grid.

3. The studied system modeling

In this paper, the studied system is a wind farm with 20 wind turbines. The capacity of each of these wind turbines is 2.5 MW. Generally, the overall capacity of the wind farm is 50 MW. In addition, along with this system, a flexible load with 5 MW flexibility is used. The flexible bag attempts to buy the energy when it is cheaper so that it won't have to buy it when it is in high-price times. The wind turbine used in this modeling is a Nordex N80/2500, whose power curve is shown in Table 1. The wind speed data and market price are used from Spain's market [23-25].

Table 1. Power specification- wind speed of wind turbine.

Row	1	2	3	4	5	6	7
Wind speed (m/s)	4	5	6	7	8	9	10
Output power (kW)	15	121	251	433	667	974	1319
Row	8	9	10	11	12	13	14
Wind speed (m/s)	11	12	13	14	15	16	17
Output power (kW)	1675	2004	2281	2463	2500	2500	2500
Row	15	16	17	18	19	20	21
Wind speed (m/s)	18	19	20	21	22	23	24
Output power (kW)	2500	2500	2500	2500	2500	2500	2500

3.1. System modeling

In this section of the paper, the studied system in the electricity market is modeled. First, the wind turbine is modeled using the offers for the next day market, then the difference between the generation and the instantaneous market is written. Next, equations for the flexible loads are extracted. The revenue of the wind power generation company and the elastic load is calculated in three modes, i.e., both discrete, continuous, and considering or not considering the uncertainty in the constant modes.

3.2. Imbalance modeling

The prediction error which leads to the power difference between the generator and the consumers in an instantaneous market is called imbalance. It might be difficult for market operators to compensate for the shortage or excess of power in the instantaneous market. Hence, any unsupplied power is purchased at a far higher price than the next day's market in the primary market, and likewise, any excess energy is sold at a lower price. If $\pi_{up,t}$ and $\pi_{down,t}$ are power excess and shortage in the primary market, respectively, $\pi_{up,t} \leq \pi_{DA,t} \leq \pi_{down,t}$ inequality can be written for them, and balancing costs in the instantaneous market can be stated as follows:

$$R(\Delta P) = \begin{cases} \pi_{up,t}\left(P_{GEN,t} - P_{DA,t}\right) & if \quad P_{GEN,t} \geq P_{DA,t} \\ \pi_{down,t}\left(P_{GEN,t} - P_{DA,t}\right) & if \quad P_{GEN,t} < P_{DA,t} \end{cases} \quad (1)$$

Where, $P_{GEN,t}$ and $P_{IM,t}$ are real generated power at the moment and the next day market, respectively. Considering the coefficients $\alpha_{up,t} \leq 1$ and $\alpha_{down,t} \geq 1$ for balancing, the following equation can be stated:

$$\pi_{up,t} = \alpha_{up,t}\pi_{DA,t}, \pi_{down,t} = \alpha_{down,t}\pi_{DA,t} \quad (2)$$

Replacing Eqs. (1) and (2), we have:

$$R(\Delta P) = \begin{cases} \alpha_{up,t}\pi_{DA,t}\left(P_{GEN,t} - P_{DA,t}\right) \; if & P_{GEN,t} \geq P_{DA,t} \\ \alpha_{down,t}\pi_{DA,t}\left(P_{GEN,t} - P_{DA,t}\right) \; if & P_{GEN,t} < P_{DA,t} \end{cases} \quad (3)$$

3.3. Wind turbine model in the market

In this section, the modeling section of a wind turbine in the electricity market is done. Considering the instantaneous market, imbalance price (the difference) and uncertainty of revenue of wind turbine in a period can be written as follows:

$$BEN_{WT} = BEN_{WT,DM} + BEN_{WT,UN} \quad (4)$$

Where, BEN_{WT} is the total revenue of the wind generation company, $BEN_{WT,DM}$ is wind generation company's revenue obtained from offering price for the instantaneous market in the next day, and $BEN_{WT,UN}$ is the received obtained from an imbalance in the primary market. However, the value of each of these revenues can be positive or negative because of the imbalance. Each of these revenues can be stated as follows:

$$BEN_{WT,UN} = \sum_{s\in S}\rho_s\sum_{t\in T}\begin{bmatrix} \alpha_{up,t}\pi_t\left(P_{WT,t} - P_{WT,DM,t}\right)u_{ub,WT,t} + \\ \alpha_{down,t}\pi_t(P_{WT,t} - P_{WT,DM,t})(1 - u_{ub,WT,t}) \end{bmatrix} \quad (5)$$

Where π_t denotes the price of 1 MW of power in the next day market. $P_{WT,DM,t}$ and $P_{WT,t}$ indicate the offered amount of wind power in the next day market and the actual generated power of wind turbine, respectively. $\alpha_{up,t}$ and $\alpha_{down,t}$ are coefficients of power excess and power shortage based on the instantaneous market of the same day. This means that the immediate market price is written based on the coefficient of the next day's market. For this purpose, if the amount of offered power in the last day market is higher than that of in the appointed time, the excess energy is sold at a price of $\alpha_{up,t}\pi_t$, and if the provided power is lower than the actual generation, the price of the remaining power is calculated based on $\alpha_{up,t}\pi_t$. $u_{ub,WT,t}$ is a binary variable, which is zero or one. If the real generation is higher than the offered amount, $u_{ub,WT,t}$is 1, and otherwise, it is zero. $\rho_s$is a probability of occurrence of s-th scenario.

3.4. Flexible load model in the offered market

Energy storage in the market is modeled so that if the price estimation is high, it sells the energy to the grid, and if the energy price is low, it buys the energy from the market. The considered model for this system can be stated as below:

$$BEN_{DR} = \sum_{s\in S}\rho_s\sum_{t\in T}\begin{bmatrix} \alpha_{up,t}\pi_t\begin{pmatrix} \Delta P_{DR,up,t} - \frac{1}{2}\times \\ \frac{1}{\beta \times D_{t,0}} \times \Delta P_{DR,up,t^2} \end{pmatrix}(u_{ub,DR,t}) \\ \alpha_{down,t}\pi_t\begin{pmatrix} \Delta P_{DR,down,t} - \frac{1}{2}\times \\ \frac{1}{\beta \times D_{t,0}} \times \Delta P_{DR,down,t^2} \end{pmatrix}(1 - u_{ub,DR,t}) \end{bmatrix} \quad (6)$$

In the equation above, $\Delta P_{DR,up,t}$and $\Delta P_{DR,down,t}$ are power shortage and power excess, respectively, by the flexible load in an instantaneous in time t. $u_{ub,DR,t}$ is a binary value that shows the relationship between power shortage and power excess.

3.5. Objective function and limits

The overall objective function for optimizing and determining the amount of offer to the market from wind turbines and energy storage is obtained through union of wind generation and energy storage companies and written as follows:

$$BEN_{SYS} = BEN_{WT} + BEN_{DR} \quad (7)$$

The equation above should be optimized, and the optimum value for the desired sources should be obtained so that their revenue is maximized. Eqs. (8) and (9) demonstrate the load variation limit in specific hours. Coefficients η_1 and η_2 are coefficients related to these variations, assumed 5% in this problem. Eq. (10) shows that the overall variations in one period, and each scenario is zero. This is because the flexible load changes its time of usage, and the load consumption is fixed. In addition, Eq. (11) shows the amount of variation, which is equal to actual consumption minus offered consumption.

$$\Delta P^s_{DR,t} \geq (\eta_1 - 1)P_{t,0} \quad (8)$$

$$\Delta P^{s}_{DR,t} \leq \eta_2 P_{t,0} \quad (9)$$

$$\sum_{s\in S}\sum_{t\in T} \Delta P^{s}_{DR,t} = 0 \quad (10)$$

$$\Delta P^{s}_{,t} = P^{s}_{DR,t} - P_{t,0} \quad (11)$$

$$0 \leq P^{s}_{WT,t} \leq P^{max}_{WT,t} \quad (12)$$

The power limit for the wind turbine generator, which indicates that the wind turbine cannot generate less than or higher than specific amounts, should be stated along with these limits. This limit is imposed by Eq. (12).

3.6. Objective function optimization procedure

The following stages optimize the objective function and offer price to the next day market to offer an optimum cost.

First stage: prediction of price for the next day market and imbalance markets and creation of different scenarios using the extent of prediction errors in the previous days

Second stage: price prediction for the imbalance market and creation of different scenarios using the extent of error in prediction

Third stage: prediction of the amount of wind generation for the next day and creation of scenarios and their probability based on the prediction records

Fourth stage: replacing the generated values in stages 1 to 3 in the written objective function and maximizing the revenue based on the current limits

Fifth stage: offering the price to the next day market for a generation (The revenue can be calculated for the microgrid on the mentioned day).

4. Results and discussion

In this section of the paper, the simulation results of the proposed structure for the participation of wind turbine and flexible load in the first week of January 2011 and forms of outputs with complete details for two days of 2011.01.01 and 2011.04.01 in Spain's market are presented. Next, these results are compared to those of other methods, and the efficiency of the proposed method is shown. To achieve this, the wind speed and market price for the next day are predicted. First, the previous years' data from Spain's market is extracted, and the desired fuzzy-neural network is trained. Training methods and the creation of different scenarios are comprehensively explained in reference [26]. Next, different wind speed scenarios and market prices are created for one-month results prediction output. This paper considers ten other conditions with ten wind generation states and ten different prices for each of the mentioned cases. Under this circumstance, 100 cases will be simulated. However, the price offer is shared between the generation company and the consumer. This means that when the instantaneous market price is very high and economical for the load to decrease consumption, the bag will prevent the wind generation company from experiencing financial loss. In addition, if the price is low in the market, the load decreases its consumption and receives the power from the excess power of the wind turbine.

The simulation results of this simulation for the two days of 2011.01.01 and 2011.04.01 are presented in Figs. 1 and 2. The first section of these results shows the amount of flexible load variation throughout the day, Market price the next day, and predicted price. The second figure shows the actual and estimated amount of wind generation for the next day's market. The overall result and revenue of the whole set for the mentioned week are shown in Fig. 2. In addition, the payment of wind turbines and flexible load are separately presented.

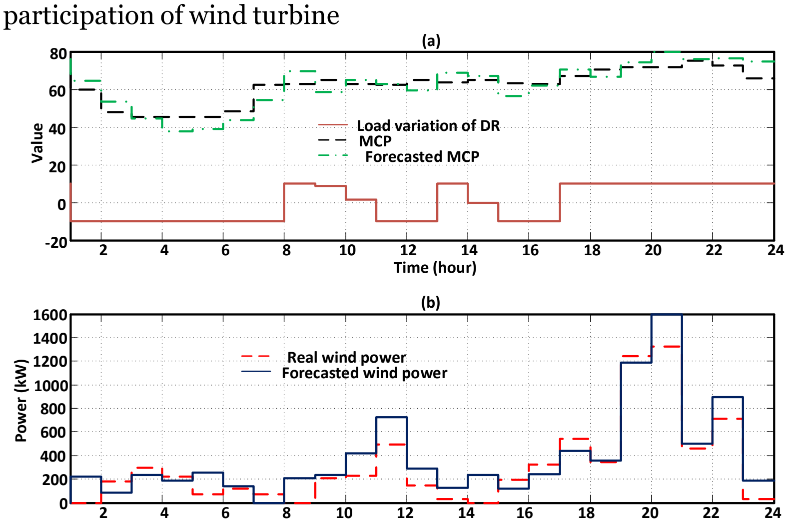

Fig. 1. The obtained results for the day of 2011.01.01 a) load and price variation b) wind farm power.

However, to further clarify the performance of the proposed method, it is better to consider other ways too and compare the proposed method's profit and loss with different scenarios. For this reason, this scenario is reached in three cases.

First case: wind turbine and flexible load each present their offers to the market separately, and the shared profit and loss are not considered. In addition, uncertainty is not considered either.

Second case: the wind turbine and the load act together and share their profit and loss, but uncertainty is still not considered.

Third case: the conditions are offered in which the interests of wind turbine and load are shared, and uncertainty is considered.

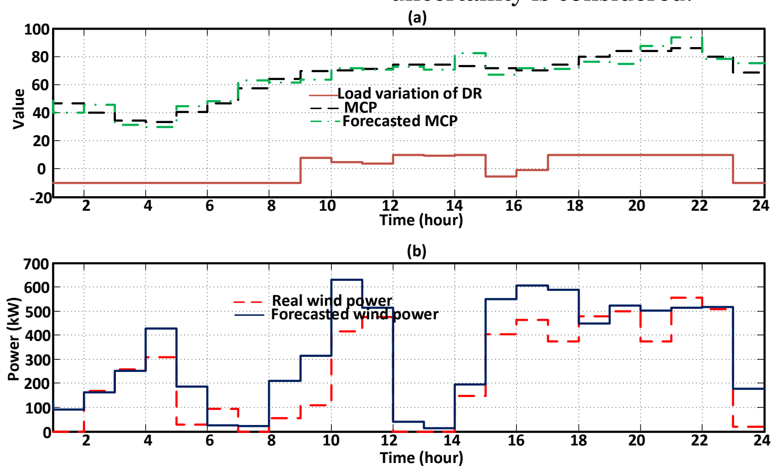

Fig. 2. the obtained results for the day of 2011.04.04 a) load and price variation b) wind farm power.

The simulation result for a week study is presented in Table 2 using the proposed strategy. This table shows the system profit for both wind turbine and load separately. In order to show the performance of the proposed strategy, the various scenarios are simulated, and the results are separately presented in Tables 3, 4 and 5 for a wind turbine, flexible load, and the whole system. Comparing these three scenarios suggests that each generation company's profit and the entire system are better in the proposed conditions than other scenarios. These results reveal that profit in wind turbine, load and the whole system in the scenario that does not consider uncertainty and the offers are separate is far less low than the other two scenarios. In this scenario, the total profit of turbines, load, and the whole system in the mentioned week are 56835.79, 1433.171, 58268.96 dollars, respectively, in one week. But these amounts for the case in which the offers are separate but uncertainty is not considered are 71.538.16, 1441.64, and 72979.8 dollars, respectively, in one week. Moreover, offering prices together, these profits are 71570.603, 1459.7561, and 73030.4, respectively.

Table 2. The obtained profit for the desired system in the third scenario.

Day of the week	Wind turbine profit	Load profit	Total profit of wind turbine and load
2011.01.01	12272.037	167.26	12439.3
2011.02.01	9818.074	174.58	9992.66
2011.03.01	9632.09	168.25	9801.15
2011.04.01	10694.87	305.23	11000.1
2011.05.01	12201.85	212.59	12414.4
2011.06.01	8501.56	174.22	8675.79
2011.07.01	8449.30	257.62	8706.9
Total sum	71570.59	1459.75	73030.3

Table 3. The obtained profit for a wind turbine in different scenarios.

Day of week	Wind turbine profit in first scenario	Wind turbine profit in second scenario	Wind turbine profit in third scenario
2011.01.01	10295	12268.35	12272
2011.02.01	7643.86	9812.68	9818
2011.03.01	7382.35	9627.9	9632.9
2011.04.01	8252.45	10688.47	10694.87
2011.05.01	10280.45	12198.47	12201.85
2011.06.01	6199.18	8498.13	8501.56
2011.07.01	6782.44	8444.16	8449.3
Total sum	56835.8	71538.16	71570.6

Table 4. The obtained profit for a wind turbine in different scenarios.

Day of week	First scenario	Second scenario	Third scenario
2011.01.01	152.12	153.38	167.26
2011.02.01	177.82	179.1	174.58
2011.03.01	171.42	172.77	168.25
2011.04.01	299.29	300.52	305.23
2011.05.01	199.41	200.72	212.6
2011.06.01	172.77	173.83	174.22
2011.07.01	260.45	261.3	257.6
Total sum	1433.29	1441.64	1459.75

Table 5. The obtained profit for the whole system in various scenarios.

Day of week	First scenario	Second scenario	Third scenario
2011.01.01	10447.16	12421.73	12439.3
2011.02.01	7821.69	9991.78	9992.66
2011.03.01	7553.77	9800.67	9801.15
2011.04.01	8551.74	10989	11000.1
2011.05.01	10479.75	12399.2	12414.4
2011.06.01	6371.95	8671.96	8675.79
2011.07.01	7049.82	8705.46	8706.9
Total sum	58268.56	72979.8	73030.3

5. Conclusion

In this study, a method is presented to increase the profit of distributed wind generation in the restructured system. To increase the profit of wind generation companies and consumers with flexible loads, they are proposed to share their prices. In addition, for this purpose, a robust estimation method of a neural-fuzzy network is used for prediction such that the imbalance associated with losses is decreased. Moreover, the uncertainty is also considered for price and wind speed, and the probabilistic method is used for optimization. The supposed system is accurate and uses wind and price information from Spain's market. The integrated model is proposed for wind turbines and demand response in day-ahead and imbalance markets. At a high market price, the wind turbine transfer more of its productions to the main grid, and the demand response is to reduce its power as its elastic factor. At a low market price, the wind turbine compensates for the demand response loads and saves virtual power in demand response to get more benefits. In the results of this paper, the three scenarios are considered as alone proposed, integrated proposed, and considering uncertainties for market price and production in integrated offering condition. The economic results for various scenarios are simulated, and the results show that the third scenario, as an integrated offering strategy with considering uncertainties, is the economical scenario and shows the high efficiency economically.

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