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Published in:
Proceedings of IEEE PES Innovative Smart Grid Technologies 2015 Asian Conference, Bangkok, Thailand, Nov 2015

DOI (link to publication from Publisher):
10.1109/ISGT-Asia.2015.7387083

Publication date:
2015

Document Version
Accepted author manuscript, peer reviewed version

Stochastic Optimal Regulation Service Strategy for a Wind Farm Participating in the Electricity Market

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***Abstract*— As modern wind farms have the ability to provide regulation service for the power system, wind power plant operators may be motivated to participate in the regulating market to maximize their profit. In this paper, an optimal regulation service strategy for a wind farm to participate in the regulating market is proposed. The relationship between up regulation price and wind power level, and the relationship between the probability of up regulation and the wind power level are studied. The stochastic optimization is adopted to find the optimal ratio for regulation service. The Monte Carlo method is used in the stochastic optimization to deal with the uncertainty of the up regulation price and the up regulation activation of the power system. The Danish short-term electricity market and a wind farm in western Denmark are chosen to evaluate the effect of the proposed strategy. Simulation results show the proposed strategy can increase the revenue of wind farms by leaving a certain amount of wind power for regulation service.**

Keywords—Wind farm; optimal regulation service strategy; stochastic optimization; regulating market; revenue maximizing

I. INTRODUCTION

The wind power industry developed very fast around the world. At the end of 2014, the new global total installed wind capacity was 369.6 GW, representing cumulative market growth of more than16% [1]. In Denmark, the wind energy accounted for 39.1% of Denmark's electricity needs in 2014 [1]. With this high level of penetration of wind power, the power system faces more severe instability issues because of the wind variation. Thus the wind powers are expected to behave as other generation sources to contribute to the power system stability.

The stability of power systems should be maintained in both the short and long term. The imbalance between load and generation is balanced by operational reserves, which are divided into primary reserve, secondary reserve and long-term reserve [2]. Variable speed wind turbines in modern wind power plants have intrinsic fast ramping up and down capabilities [3, 4], so they are able to provide primary reserve and secondary reserve [5]. The secondary reserve is also called regulating power, which can be traded in the regulating power market where the players submit their bids for upward and downward regulation of production or consumption [2].

In Nordic countries, wind power can be traded in the Nordic electricity market, which consists of three markets: the spot market, the balancing market and the regulating market [6]. The spot market is a day-ahead market where power contracts of a minimum of one-hour duration are traded for delivery of the following day [7]. The balancing market is an intraday market [8]. It closes one hour before the physical delivery and the participants can trade in this market in the intervening hours to improve their physical electric balance. However, this market is not very active [9]. The regulating market serves as a tool for system operators to balance the power generation to the load at any time during real-time operations [10]. There are two kinds of bids at each hour: the up regulation and the down regulation.

Many researches focus on the bid strategy in the spot market [11-14]. During real-time operations, the penalty for over-generation is often less than the spot market price, thus the wind power plant operators (having close to zero marginal cost) tend to maximize their profit by outputting all of its available wind power [15]. Reference [15] proposes a combined energy and regulation reserve market model to allow wind producers to participate in the regulation reserve market with lower deviation penalties. Reference [6] proposes an optimal bidding strategy for trading wind power in the short-term electricity market. Stochastic optimization is adopted in order to deal with the uncertainty of the regulation price, the activated regulation of the power system and the forecasted wind power generation.

As modern wind turbines have the ability to provide regulation service control [5], it is natural for the wind power plant operators to derate a certain amount of energy to participate in the regulating market to maximize their profit. And it is also because the up regulation price is always greater than the spot price. However, it is not clear that how much energy should the wind farms derate at each hour.

In this paper, the optimal regulation service strategy for a wind farm to participate in the regulating market is researched. The spot market bidding strategy is not considered and all the available wind energy except the energy for regulation service is traded in the spot market, because the penalty for over-

This research work is supported by the Danish Strategic Research Centre (Grant DSF 09-067255), "Development of a Secure, Economic and Environmentally-friendly Modern Power System" (SEEMPS)

generation is always less than the spot market price and wind power plant operators have almost zero marginal cost. The down regulation is also not considered because the down regulation price is always lower than the spot market price. Therefore all the wind energy for regulation service is assumed to be used for up regulation. Stochastic optimization and the Monte Carlo method are adopted to deal with the uncertainty of the up regulation price.

This paper is organized as follows: Section II describes the relationship between up regulation price and wind power level. Section III shows the formulation of the optimization problem and the stochastic optimization method used to solve the problem. The effect of the new strategy is illustrated in Section IV, and finally conclusions are drawn in Section V.

II. Relationship Between Up Regulation Price and Wind Power Level

The spot price and up regulation price is volatile and is changing with time. The data of them in the western Denmark area can be obtained from Energinet.dk [16]. Fig. 1 shows the spot price and up regulation price of western Denmark in a period of the year 2008. The time interval of these data is one hour. It can be seen that the up regulation price is always higher or equal to the spot price, which aims to encourage the participants to consume less electricity and generate more electricity.

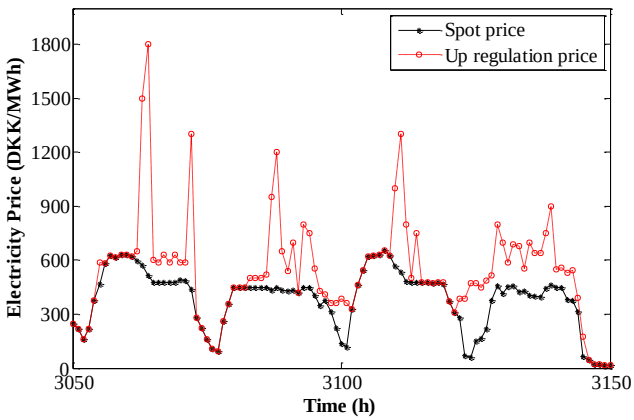

Fig. 1. The spot price and up regulation price of western Denmark in a period of the year 2008

Actually, the spot price and up regulation price variate with the wind power level, as shown in Fig. 2. The wind power level in this figure is the ratio of hourly wind power to the installed capacity of the wind power in Denmark. The wind power level is divided with the interval of 10% and the electricity price is the mean value of all hourly prices in each range. It can be observed that the deviation of up regulation price decreases with the increase of wind power level. The reason is that the power system operator needs less generation with a higher wind power level.

The probability of up regulation activation with the change of wind power level is shown in Fig. 3. At lower wind power level, the probability of up regulation is higher because the power system needs more generation and less loads at lower wind power level.

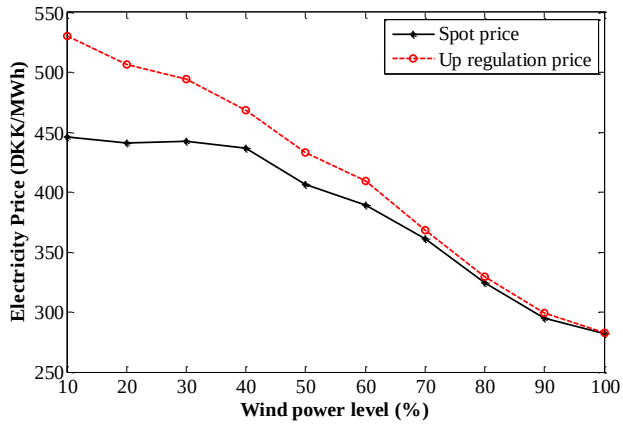

Fig. 2. The variation of spot price and regulation price with the change of wind power level in the year 2008

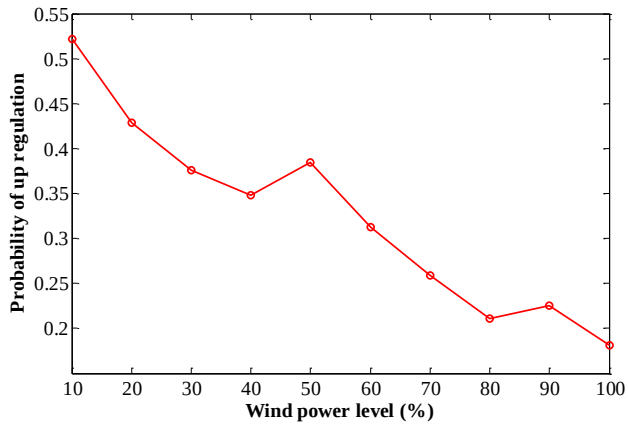

Fig. 3. The probability of up regulation activation with the change of wind power level in the year 2008

The relationship between the up regulation price and wind power level and the relationship between the probability of up regulation and wind power level are useful for making the regulation service strategy for wind farms. In the next section, stochastic optimization method is used to find the optimal regulation service strategy based on the relationships between the electricity price/probability of up regulation and wind power level.

III. Stochastic Optimal Regulation Service Strategy

In this section, a stochastic optimal regulation service strategy is proposed to maximize the revenue of the wind farm. The Monte Carlo method is used in the stochastic optimization to deal with the uncertainty of the up regulation price and of the up regulation activation of the power system.

A. *Problem formulation*

In the spot market, the penalty for over-generation is always less than the spot market price and wind farms have almost zero marginal cost, so it is reasonable to assume that all

the available wind power except the portion for regulation service is traded in the spot market. Meanwhile, all wind power for regulation service is assumed to be used for up regulation. In the real-time regulation market, wind farm operators may only be motivated to participate in the up regulation, because the down regulation price is usually lower than the spot price and the wind farm operators want to maximize their revenue. It is also assumed that the available wind power in an hour is known beforehand, i.e., the prediction of wind power in an hour is accurate.

There are some facts that also need to be stated. The spot market is a day-ahead market and the spot price is known 24 hours before the operation hour. And the regulation power in Denmark is usually paid both as a reservation price (fixed capacity price) and an activated price (up regulation price) [17]. The current fixed capacity price is 10 million DKK per month, and the amount of regulation power is 90 MW, so the fixed capacity price for per MW power per hour is 154 DKK [18].

Based on the assumptions and facts, the revenue of a wind farm in an hour can be formulated as:

$$R = E_w(1-\alpha)P_{spot} + E_w\alpha(P_{up} + P_{cap})\beta_{up} \quad (1)$$

$$\alpha = E_{up} / E_{avail} \quad (2)$$

Where R is the revenue of the wind farm, E_w is the amount of the available wind power in an hour, P_{spot} and P_{up} are the spot price and up regulation price, P_{cap} is the fixed capacity price, β_{up} is the probability of up regulation activation, E_{up} and E_{avail} are the wind power for up regulation and the available wind power, and α is the derating ratio of the de-rated power to the available wind power.

B. Stochastic Optimization method

The aim of this paper is to maximize the revenue by finding the optimal derating ratio for the wind farm. The available wind power, the spot price and fixed capacity price are assumed to be known beforehand. However, the up regulation price and the probability of up regulation activation are still uncertain. Therefore, stochastic optimization and the Monte Carlo method are adopted to deal with the uncertainty of the up regulation price and the probability of up regulation activation.

Fig. 4 shows the process of stochastic optimization. Firstly, the derating ratio is initialized to be zero. Then, the zone of wind power level is decided. In the judged zone of the wind power level, the up regulation price and probability of up regulation activation are generated based on the probability density of up regulation price and up regulation activation in the Danish electricity market, which has been shown in Fig. 2 and Fig. 3. The revenue of each set can then be calculated by (1). In the Monte Carlo method, 1000 sets of data of the up regulation price and the probability of up regulation activation are generated. The interior point method [19] is used to solve the nonlinear optimization problem. The method makes a lot of iterations until the stop criterion is satisfied. And the wind energy derating ratio is constrained as [0, 0.2] because higher derating ratio will cause much higher load on the wind turbines [5], thus causes too much load on the wind turbines.

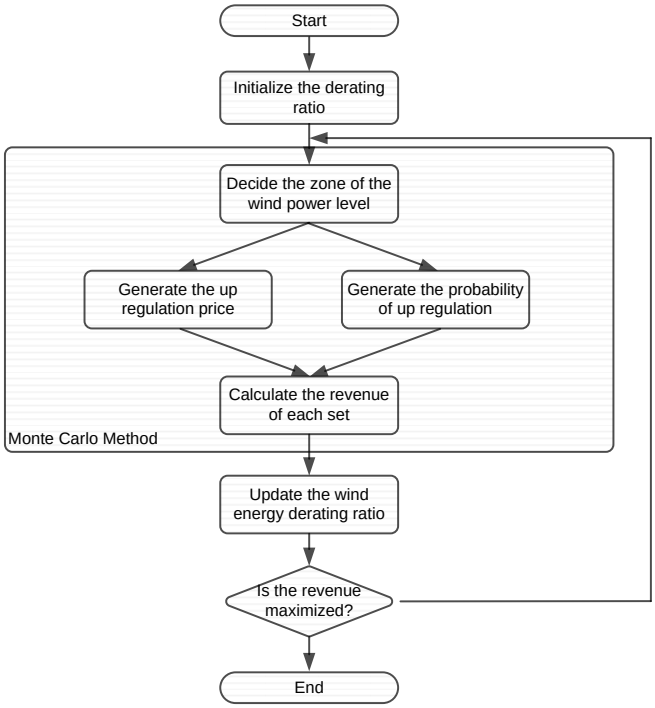

Fig. 4. The process of the stochastic optimization

IV. CASE STUDY

A wind farm in western Denmark is used for the case study. The actual wind power data is collected in the year 2008. The wind power level of the wind farm at each hour in a single day is shown in Fig. 5. It can be seen that within this day, the wind power level is between 10% and 20%. The hourly spot price and hourly up regulation price in western Denmark is collected on the same day, as shown in Fig. 6. The up regulation price at each hour in that day is always higher than the spot price and the highest electricity price appears around the dinner time. Fig. 7 shows the up regulation activation in western Denmark at each hour in that day. It can be seen that the up regulation is always activated except the hour 9 and 10.

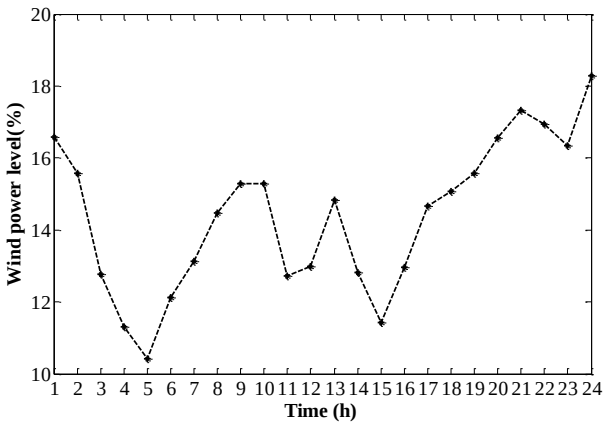

Fig. 5. The wind power level of the wind farm at each hour in a day

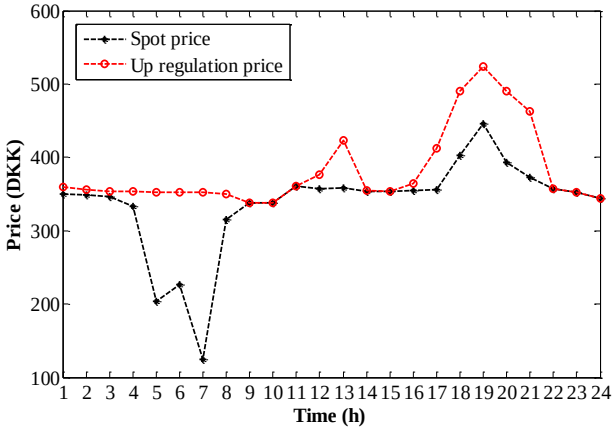

Fig. 6. The spot price and up regulation price in western Denmark at each hour in a day

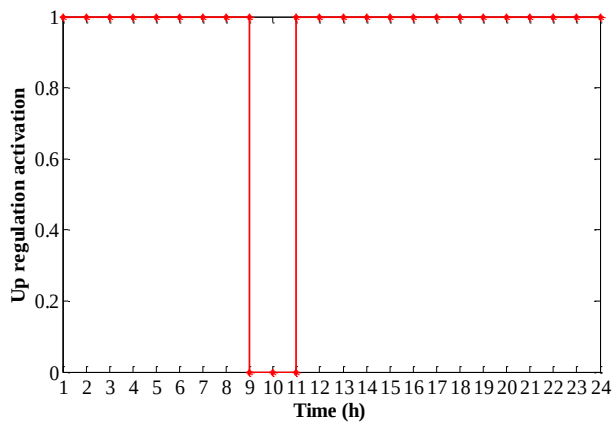

Fig. 7. The up regulation activation in western Denmark at each hour in a day

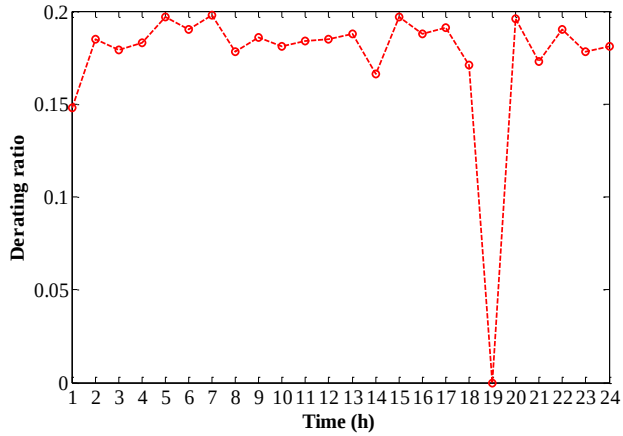

Fig. 8. The optimal derating ratio for the wind farm at each hour in a single day

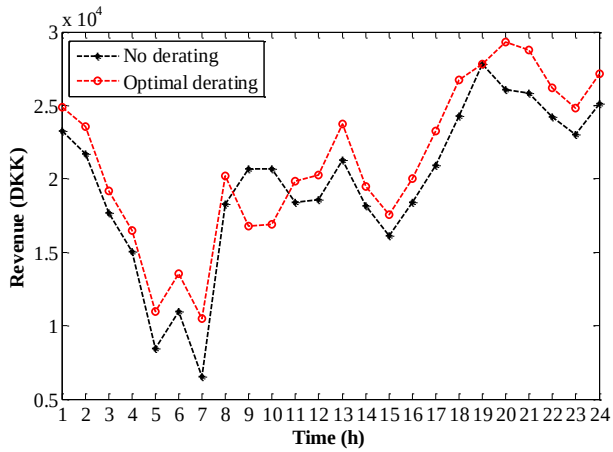

Fig. 9. The revenue of the wind farm with derating and without derating at each hour in a day

The optimal wind power derating ratio at each hour is calculated using the stochastic optimization and the results are shown in Fig. 8. The derating ratio is within the limits and varies with time. At hour 19, the derating ratio is zero, however the up regulation price is much higher than the spot price at this hour, see Fig. 6. The reason is that what is shown in Fig. 6 is the actual up regulation price, however in the real-time operation, they are not known beforehand, so we use the Monte Carlo method to generate the up regulation price and probability of up regulation activation based on the probability density of the zone where the wind power lies in. Therefore, the generated up regulation price may be different from the real value, which makes the strategy worse at some points.

The revenue of the wind farm with derating and without derating at each hour in a day is illustrated in Fig. 9. The proposed strategy can increase the revenue of the wind farm most of the time. However, the revenue is decreased at hour 9 and 10, which is also because of the deviation of stochastic optimization. At hour 19, there is no revenue increase, because the derating ratio is zero, see Fig. 8. It also can be observed from Fig. 9 that the total revenue in a day is increased using the proposed strategy.

In order to further evaluate the effect of the proposed strategy, the revenue of the wind farm at each wind power level is calculated with derating and without derating. The revenue at every hour in the year 2008 is calculated and is averaged in each zone of wind power level. The results are shown in Fig. 10. It can be seen that at every wind power level, the proposed strategy can increase the revenue of the wind farm. Fig. 11 shows the revenue increment of the wind farm with derating. It can be seen the revenue increment is larger at high wind power level, which is mainly because the amount of energy is higher at high wind power level.

The revenue of per MWh wind power at each wind power level is calculated with derating and without derating, and is listed in TABLE I. It can be seen that the revenue increment of per MWh wind power is the highest when wind power level is 10%. At this wind power level, the revenue increment is 3.61 DKK for per MWh energy, which accounts to 0.81% of the revenue of per MWh energy without derating. The wind power derating ratio at this wind power level is also the highest, at 0.143. The derating ratio tends to decrease with the increase of wind power level, which is mainly because the up regulation price and the probability of up regulation decrease with the increase of wind power level, see Fig. 2 and Fig. 3.

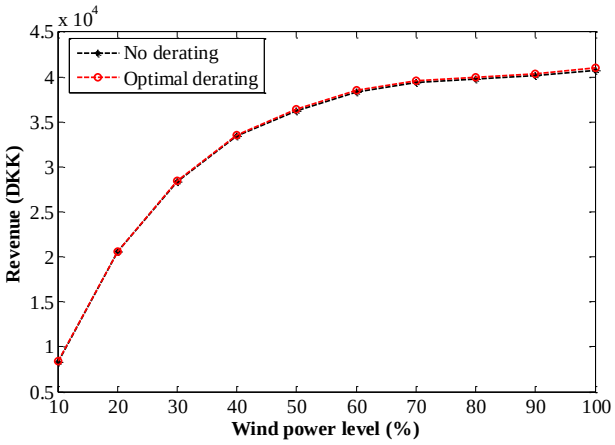

Fig. 10. The revenue of the wind farm with derating and without derating at each wind power level

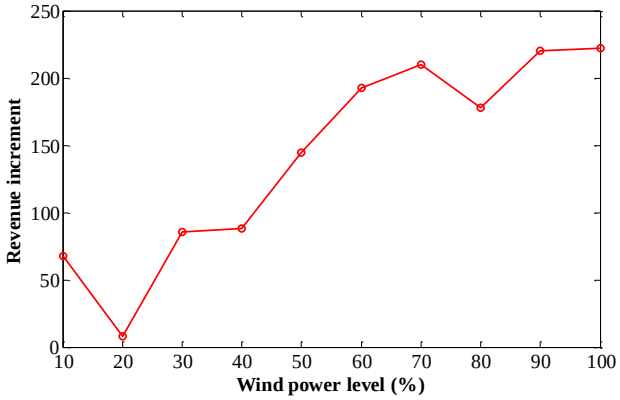

Fig. 11. The revenue increment of the wind farm with derating at each wind power level

TABLE I. THE REVENUE OF PER MWH WIND POWER WITH DERATING AND WITHOUT DERATING AT EACH WIND POWER LEVEL

Wind power level	**10%**	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Revenue without derating (DKK)	446	349	287	240	203	175	151	133	118	108
Revenue with derating (DKK)	450	349	288	241	204	176	152	134	119	109
Revenue Increase (DKK)	3.61	0.14	0.87	0.63	0.81	0.88	0.81	0.60	0.65	0.59
Increase Ratio	0.81%	0.04%	0.30%	0.26%	0.40%	0.50%	0.53%	0.45%	0.55%	0.54%
Derating ratio	0.143	0.105	0.093	0.088	0.091	0.090	0.089	0.088	0.090	0.089

V. CONCLUSION

The optimal regulation service strategy for a wind farm to participate in the regulating market is researched and validated in this paper. The relationship between up regulation price and wind power level and the relationship between the probability of up regulation and the wind power level in western Denmark are studied. Some assumptions are made to define the revenue model and the actions of a wind farm in the Nordic electricity market. Stochastic optimization and the Monte Carlo method are adopted to deal with the uncertainty of the up regulation price and the probability of up regulation activation. The test in a wind farm in western Denmark validated the proposed strategy can increase the revenue by reserving a certain amount of wind power for regulation service. Future work would include the cost of wind power derating into the objective function.

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