Bidding method for wind generation company in nodal power market

Yangyang Liu¹, Tianen Chen², Jianxue Wang¹, Yan Li², Yunhao Li¹, Ruifeng Liu²

¹School of Electrical Engineering, Xi’an Jiaotong University, Xi’an 710049, People’s Republic of China
²Northwest Branch of State Grid Corporation China, Xi’an 710048, People’s Republic of China
E-mail: 1248619915@qq.com

Published in The Journal of Engineering; Received on 6th October 2017; Accepted on 2nd November 2017

Abstract: In recent years, the increasing integration of wind power has become a critical issue in power system. Owing to the randomness and intermittency of wind generation, it is a big challenge to incorporate wind power into power market operation fairly. To address this challenge, a novel method is presented for wind generation companies to bid in a nodal power market. Wind power output is comprised of two parts, i.e. reliable energy part and uncertain energy part. In the nodal power market, reliable energy bids in single price mode. On the other hand, uncertain energy bids in two-part price mode; which contains adjustment price and energy price. According to the above remarkable features, the authors’ research develops the mathematical model for wind power bidding and design the corresponding market clearing mechanism. Also, the impact of their method on wind power accommodation and social benefit is deeply analysed. Numerical results indicate that the proposed method enables the fair competition among renewable energy generation company in the electricity market; thus, could enhance the integration of wind power while alleviating on providing a subsidy.

Nomenclature

\[ N_w \] number of wind generating units in the system
\[ N_t \] number of traditional generating units in the system
\[ N_l \] number of loads
\[ C_{w,i} \] offer price of风 power generating unit \( i \)
\[ C_{t,i} \] offer price of traditional generating unit \( i \)
\[ P_{w,i} \] wind power output of wind generating unit \( i \)
\[ P_{t,k} \] power of forecated load \( k \)
\[ P_{w} \text{max} \] maximum power of wind power generation
\[ P_{t}\text{max} \] maximum power of traditional generation
\[ P_{i}\text{min} \] minimum power of traditional generation
\[ P_{i}\text{max} \] maximum power of traditional generation
\[ P_{l}\text{max} \] maximum power of line
\[ P_{w,i}\text{max} \] power of wind generating unit \( i \) in AJ market
\[ P_{t,i}\text{max} \] power of traditional generating unit \( i \) in AJ market
\[ \lambda \] Lagrange multiplier of power balance constraint
\[ \mu_i \] Lagrange multiplier of line power limit constraint

1 Introduction

The intensification of environmental problems leads to the rapid development of wind power generation. Since wind is free and inexhaustible fuel without any emissions, it is regarded as a perfect alternative to traditional fossil fuels. According to the statistics, the total installed global capacity of wind power reached 486.8 GW at the end of 2015 [1]. However, certain issues should be considered seriously for high penetration of wind power has a great impact on the operation of power system. Integration of wind power poses a great risk to the reliability of power system and power market, because of its uncertainty and variability. Researchers explore numerous strategies in order to fully utilise wind generation and reduce wind curtailment which is described in [2].

A new method for wind power forecasting based on Gaussian process is proposed to reduce the uncertainty of wind power output and enhance the stability of power system [3]. Since the contribution of improving prediction accuracy is limited due to the restriction of mathematical technique, researchers and power system operators try new ways from another perspective. Energy storage system (ESS) attracts increasing attention, because the combination of wind generation and ESS can lead to various benefits to power system [4, 5].

However, only a small number of researches concentrate on the market-based approach to solve this issue promoting wind power consumption. The market is a fair and effective way to some extent. In traditional energy markets, wind power generations do not participate in the market, and it is treated as a negative non-responsive load. We call these wind power generations ‘price taker’, i.e. they have no market power to influence price formation, while accepting the price derived from the energy market. To prevent the wind power generation companies from not meeting power balance of system, researchers propose a new approach called risk-limiting dispatch by considering the stochastic nature of wind [6]. This approach has a great issue to be taken into account, i.e. it will be unreasonable to assume that the wind generation companies have no market power when their penetration is high. Wind generation companies must bid in energy markets such as other classical power generations to form a proper price in this condition.

To design an appropriate market mechanism becomes a critical problem operators have to solve. In [7–9], researchers study the design of an energy market and the formation of energy price. However, all of these papers concentrate on the classical generation, renewable energy such as wind power is rarely involved.

We note that increasing wind generations installed lead to power system transmission congestion in addition to power balance...
problem. Locational marginal price (LMP) is an effective method to solve this problem; it consists of energy cost, congestion cost and loss cost. The different buses have its own LMPs, the differences between buses can relieve transmission congestion naturally. It is beneficial for wind generation company to be allowed to participate in LMP-based markets (nodal markets), from an economical perspective and reliability perspective [10]. The New York Independent System Operator (ISO) and the Midwest ISO take their own measures to allow operators optimise the dispatch of wind generation based on security and economics of power system [11, 12].

In this paper, a novel bidding method for wind generation companies in nodal power market is proposed and this paper designs the operation of LMP-based adjustment energy market. Results proved that this new method can reduce operation cost and utilise wind power effectively.

This paper is organised as follows. Section 2 mainly discusses why we should divide wind output into two parts and how we design an adjustment energy market based on LMP. In Section 3, how wind generation companies bid in the energy market and the operation of LMP-based adjustment market. Section 4 shows results of analysis of the proposed model. Conclusions are drawn in Section 5.

2 Proposed methodology

One of the most critical factors that influence the utility of wind power is its stochastic output. The deviations between expectation and actual output can lead to trouble to the operation of power system. While not all of the wind powers are random, i.e. certain part of wind generation output is reliable, especially in some regions with rich wind resources, wind power output can ensure a minimum value. From Fig. 1, we can see that different output blocks divided by red line have a different value in the same period for their various reliabilities. Moreover, the same output level has a different value in different periods. We divided wind generator output into two parts in this paper for convenience without any other impacts to the proposed model’s feasibility.

Since the reliable output is deterministic just such as classical generation, it would not do harm to the power system. We can define that this part of wind power has a high quality, and reliable part and uncertain part must be treated differently. Power with high quality is supposed to get a high price, and vice versa. In [13], Du and Wang show us a novel method to estimate the value of different parts of wind power output by layer. The proposed meticulous approach is somewhat sophisticated to use in the energy market. This paper simplifies it and designs corresponding adjustment market.

This proposed adjustment market is unique and based on LMP. Although many markets such as pennsylvania-new jersey-maryland (PJM) and UK electricity market, which have their approaches to solve the power balancing problem, while they have their own limitations. For instance, the UK electricity market keeps power balancing by ‘offer and bid’. However, this method cannot deal with the transmission congestion problem. So, this paper takes congestion cost into account and build an adjustment market based on LMP.

The designed market consists of day-ahead (DA) market and the proposed adjustment market. In DA market, wind generation companies offer only reliable part such as other classical generations. The operators need not consider deviations in DA market. Moreover, in adjustment market, wind generation company can nearly determine the accurate output. At this time, wind generation company only offers added output compared with DA reliable part. According to the above statement, the uncertain part deserves lower price. To balance the added power, traditional generation companies need to reduce their own output by returning some of the money they got in DA market. Wind power can be utilised fully and the operation cost of the power system will be cut through this way.

3 Model formulation

3.1 DA market

LMP in DA market is calculated in the traditional math model. This model is organised as follows. The objective of this model is to minimise the cost of buying electricity

\[
\min \sum_{i=1}^{N} C_{w,i}P_{w,i} + \sum_{j=1}^{N} C_{a,j}P_{a,j}
\]

Subject to:

(i) Power balance constraint

\[
\sum_{i=1}^{N} P_{w,i} + \sum_{j=1}^{N} P_{a,j} = \sum_{k=1}^{N} P_{1,k}
\]

The load demand that is supposed to be inelastic is forecasted before the day:

(ii) Transmission power constraint

\[
P_l \leq P_l^{\text{max}} \quad l = 1, 2, \ldots, L
\]

(iii) Constraints of generating units

\[
0 \leq P_{w,i} \leq P_{w,i}^{\text{max}}
\]

\[
P_{a,j} \leq P_{a,j}^{\text{max}}
\]

In the calculation of transmission power, we use \( T \) called transfer factor matrix which represents the connection between bus power and line power. Moreover, the formula is shown in (5)

\[
T(P_G - P_D) \leq P_L
\]

LMP will be available by solving the linear programming model

\[
\mu_k = \lambda + \sum_{i} \mu_k T_{ki}
\]

LMP expression is composed of \( \lambda \) and \( \mu_k \). After the solvation of this model, these Lagrange multipliers can be available. Since this
model is based on DC flow, loss cost is not contained in this formula

$$\rho_{\text{Loss},s} = \lambda \frac{\partial P_{\text{Loss}}}{\partial P_{G,s}}$$  \hspace{1cm} (7)

Loss cost part of LMP is shown in (7). $\frac{\partial P_{\text{Loss}}}{\partial P_{G,s}}$ are called incremental transmission losses, which can be calculated by AC flow model. Owing to space limitations, the process of specific speculation is not discussed in this paper.

3.2 Adjustment market

In adjustment market, the definition of LMP is different from that in DA market though the calculation model is similar

$$\min \sum_{i=1}^{N_w} (S_i P_{w,i}) - \sum_{j=1}^{N_t} (B_j P_{t,j})$$  \hspace{1cm} (8)

In (8), $S_i$ is the profit wind generator except for uncertain part of output and $B_j$ is what traditional generators are supposed to return to market because it reduces its power.

Subject to:

(i) Power balance constraint

$$\sum_{i=1}^{N_w} P_{w,i}^A = \sum_{j=1}^{N_t} P_{t,j}^A$$  \hspace{1cm} (9)

(ii) Transmission power constraint

$$P_{t,j}^A \leq P_{t,j}^\max \quad l = 1, 2, \ldots, L$$  \hspace{1cm} (10)

(iii) Constraints of generating units

$$0 \leq P_{w,i}^A \leq P_{w,i}^\max$$

$$0 \leq P_{t,j}^A \leq P_{t,j}^\max$$  \hspace{1cm} (11)

We note that (9) is somewhat different from (2). In (2), the formula means the balance between all generators’ power and load, while in (9) the balance is between the added power of wind generations and reduced power over traditional generations. The LMP expression in adjustment market is similar to what in DA market.

We proposed some assumptions in the model without any effect on its universality:

(i) Deviations between DA forecast load and real-time load are zero, i.e. the forecasted results are accurate.

(ii) In adjustment market, the maximum power wind generator company bid is supposed as real as its real output. Moreover, in the case, we assume that uncertain power of wind generator is about 40% of the reliable part. This proportion would not have an impact on the conclusion.

4 Case study

In this section, we prove the feasibility and economy of this paper’s proposed model and present a case study based on a simple three-bus system [14].

In this case, we assume the adjustment cost at a level and based on that wind generators and traditional generators all can get some profit. The assumption has no effect on the model’s general applicability.

The three-bus system as shown in Fig. 2 is composed of four conventional generators and a wind generator located at bus 3. Moreover, we can see the detailed data of these generators in Table 1. Wind power generation company has cheap cost for it nearly does not have any operation margin cost. For comparison, traditional generators are also divided into cheap cost generators and expensive generators. Adjustment cost means the cost that the generator expects if you want it to change its output cleared in DA market. Apparently, wind generator wants to raise its output, so the adjustment cost is positive, whereas the traditional generator’s adjustment cost is negative, because traditional generators reduce its output and should return some profit it got in DA market.

In Table 2, we can see detailed transmission line parameters. In this case, we concentrate on the benefit of adjustment market, so we lose sight of power loss in power system.

To illustrate the benefits of the method proposed in this paper in the nodal market, we run two simulations in a single period. The first only considers DA market, the second is composed of DA market and adjustment market (AJ market).

Tables 3 and 4 show us the results of the case. Note that cleared power of traditional generating unit in AJ market is negative and wind generating power is positive. The power purchase fee in DA market is $31.9667, while after the running of AJ market, the operation cost, i.e. the power charge reduced to $30.9617. It means that

![Fig. 2 Three-bus system](image)

| Table 1 Generator data of the power system |
|-------------------|-----|-------------|-------------|------------|
| Unit   | Type | Bus | $P_{\text{max}}$ | Energy cost, S/MWh | Adjust cost, S/MWh |
|--------|------|-----|-----------------|------------------|------------------|
| 1      | traditional | 1   | 1.4            | 7.5              | 4                |
| 2      | traditional | 1   | 2.85           | 6                | 3                |
| 3      | traditional | 2   | 0.9            | 14               | 7                |
| 4      | traditional | 3   | 0.85           | 10               | 5                |
| 5      | wind      | 3   | 0.8            | 3                | 2                |

| Table 2 Transmission line data of the power system |
|-----------------|-----|-------------|
| Line | X  | Transmission capacity, MW |
|------|----|--------------------------|
| 1–2  | 0.2 | 1.26                     |
| 1–3  | 0.2 | 2.5                      |
| 2–3  | 0.1 | 1.3                      |

This is an open access article published by the IET under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0/).
Table 3 Clearing power results of this paper

| Bus | DA price, $/MWh | AJ price, $/MWh |
|-----|---------------|----------------|
| 1   | 7.5           | 4              |
| 2   | 14            | 5.5            |
| 3   | 11.83         | 5              |

Table 4 Clearing price of this paper

| Unit | DA cleared power, MW | AJ cleared power, MW | Sum, MW |
|------|----------------------|----------------------|---------|
| 1    | 0.4667               | −0.015               | 0.4517  |
| 2    | 2.85                 | 0                    | 2.85    |
| 3    | 0.0333               | −0.03                | 0.0033  |
| 4    | 0.85                 | −0.275               | 0.575   |
| 5    | 0.8                  | +0.32                | 1.12    |

It is worth mentioning that wind generation company is likely to bid more power than it can provide deliberately to get more profits. So, a penalty mechanism is needed in this market.

6 Acknowledgment

This work was supported by the Science and Technology Project of Northwest Branch of State Grid Corporation China (no. 52993216000H).

7 References

[1] Global Wind Energy Council. Available at http://www.gwec.net/index.php?id=30&no_cache=1&tx_ttnews. Accessed June 2016
[2] Ela E., Milligan M., Parsons B., et al.: ‘The evolution of wind power integration studies: past, present, and future [C]’. 2009 IEEE Power & Energy Society General Meeting, 2009, pp. 1–8
[3] Lee D., Baldick R.: ‘Short-term wind power ensemble prediction based on Gaussian processes and neural networks’, IEEE Trans. Smart Grid, 2014, 5 (1), pp. 501–510
[4] Lu M.S., Chang C.L., Lee W.J., et al.: ‘Combining the wind power generation system with energy storage equipment’, IEEE Trans. Ind. Appl., 2009, 45 (6), pp. 2109–2115
[5] Hu P., Kaki R., Billiton R.: ‘Reliability evaluation of generating systems containing wind power and energy storage’, IET Gener. Transm. Distrib., 2009, (3), (8), pp. 783–791
[6] Rajagopal R., Bitar E., Varaiya P., et al.: ‘Risk-limiting dispatch for integrating renewable power’, Int. J. Electr. Power Energy Syst., 2013, 44 (1), pp. 615–628
[7] Johanna L., Maryam K.: ‘Arbitraging intraday wholesale energy market prices with aggregations of thermostatic loads’, IEEE Trans. Power Syst., 2015, 30 (2), pp. 763–772
[8] Andreas G., Pandelis N.: ‘Simultaneous clearing of energy and reserves in multi-area markets under mixed pricing rules’, IEEE Trans. Power Syst., 2015, 26 (4), pp. 2460–2471
[9] Cho I.–K., Meyn S.P: ‘Efficiency and marginal cost pricing in dynamic competitive markets with friction’, Theor. Econ., 2010, 5 (2), pp. 215–239
[10] Ela E., Edelson D.: ‘Participation of wind power in LMP-based energy markets’, IEEE Trans. Sustain. Energy, 2012, 3 (4), pp. 777–783
[11] Gonzales R., Mukerji R., Swider M., et al.: ‘Integration of wind into system dispatch [R]’ (ISO White Paper, New York, 2008)
[12] PJM Manual 12: ‘Balancing operations’, Attachment B. Rev., 2015, 32, pp. 1–472
[13] Du C., Wang X., Wang X., et al.: ‘Comprehensive value assessment of wind power by layer’, IEEE Trans. Power Syst., 2016, 31 (2), pp. 1238–1247
[14] Stoft S.: ‘Power system economics[M]’ (Wiley-IEEE Press, New York, U.S.A., 2002)