Risk Assessment of Electricity Price Considering Guaranteed Accommodation of Renewable Energy in Electricity Market

Siying Li¹, Maosheng Sang¹*, Jie He², Luosong Jin², Wen Zhao², Hengzi Huang² and Yi Ding¹

¹ School of Electrical Engineering, Zhejiang University, Hangzhou 310027, China
² Zhejiang Power Exchange Center Co., Ltd., Hangzhou 310016, China

*maosheng_sang@zju.edu.cn

Abstract. Renewable energy generation (REG) based on wind power and photovoltaic has become the main energy supply for the low-carbon energy transformation in China. It is an important task to guarantee the accommodation of renewable energy through the market-based mechanism. However, due to the uncertainty of REG output, the integration of a high proportion of renewable energy into power grids may bring risks to the electricity price. On the basis, this paper incorporates the guaranteed consumption of wind power and photovoltaic renewable energy into the electricity market clearing model and proposes a price risk assessment method. Firstly, the scenario generation algorithm is established to describe the uncertainty of REG output, and a representative set of limited scenarios is generated. Secondly, the clearing model of electricity market with renewable energy participation and the calculation method of nodal price are established. Then, the price risk indexes are proposed to assess the price risk caused by renewable energy uncertainty. Finally, the effectiveness of the proposed method is verified by the modified IEEE30 bus system. The findings could guide the participation of REG in the electricity market.

1. Introduction
In recent years, global climate and environmental conditions have posed a great challenge to human society. Low carbon has become an inevitable trend in the development of the energy industry around the world [1]. In the meanwhile, the energy transformation is going through a critical period with the proposal of "3060 target" in China, which promotes a high proportion of renewable energy to be integrated into power grids. By the end of 2019, the total installed capacity of wind power and photovoltaic reaches 414 GW, accounting for 20.6% of the total installed capacity. As a result, renewable energy generation (REG) based on wind power and photovoltaic gradually becomes the main energy supply form in China.

In order to guarantee the accommodation of renewable energy, the forecast output of REG usually is taken as the boundary condition for electricity market clearing models in most countries. However, the uncertainty of REG output may affect the clearing price in the real-time market, resulting in sharp price fluctuations. Therefore, with the increasing proportion of renewable energy, it is urgent to pay attention to the price risk caused by the uncertainty of REG output.

Currently, several studies have been conducted involving the price risk analysis in electricity market. [2] studies the impact of random failures of generating units or transmission lines on nodal price, and proposes quantitative evaluation indexes such as expected nodal price and expected load loss. Reference
[3] proposes the analysis methods of node price and node reliability considering emergency reserve. [4] further considers the impact of wind power, photovoltaic, and other distributed renewable energy on the node price of the electricity market, and validates the economic and environmental benefits of renewable energy on the market operation, but the scale of REG considered is small. In [5], an optimization scheme for power investment of generation companies is proposed considering the risk factors such as spot market price fluctuation and system component failures. The above-mentioned research studies have conducted in-depth research on the price fluctuation analysis and power system reliability under the electricity market environment, but few have analyzed the risk of clearing price caused by the high proportion of renewable energy participation. At present, there is still no effective and quantitative evaluation method for the price risk.

To this end, a price risk assessment method considering the participation of renewable energy is proposed in this paper. Example analysis shows that the proposed method can quantify the overall price risk of the system, and get the expected level, fluctuation, and the possibility of large value of electricity price. By improving the forecast accuracy of REG output, the uncertainty of renewable energy can be effectively reduced, and the risk of electricity price can be reduced.

2. REG output scenario generation algorithm
The uncertainty of REG output, including wind power and photovoltaic, can be characterized by the forecast error between actual values and forecast values, which is expressed as

\[ P(t) = P_{\text{meas}}(t) + \varepsilon(t) \]  

where \( P(t) \) and \( P_{\text{meas}}(t) \) are respectively the actual values and forecast values of REG output. \( \varepsilon(t) \) is the forecast error, which relates to the forecast time scales and techniques. Generally, the forecast error is assumed to obey normal distribution. For studying the effect of uncertainty on the electricity market clearing, the uncertainty level is set to be able to tune by changing the standard deviation of \( \varepsilon(t) \).

Based on the stochastic uncertainty model as shown in equation (1), a large number of REG output scenarios can be obtained. If each scenario obtained is analyzed, the calculation amount required is too large and unnecessary, so the scenario reduction needs to be carried out. The fast forward method [6] is used to reduce a large number of scenarios, so that the probability distance between the finally reserved scenario subset and the scenario set before reduction is the smallest, as shown in equation (2):

\[ \min \sum_{i,j} p_i \left( \min_{p_j} \| P_i - P_j \| \right) \]  

where \( p_i \) is the probability of scenario \( i \) of \( P_i \) and \( P_j \) are respectively the REG output series under scenario \( i \) and \( j \). \( i \) and \( J \) refer to the reduced scenario subset and the final reserved scenario subset.

Based on the above REG output scenario generation algorithm, a representative set of limited scenarios with large probability can be obtained to approximate the original scenario set.

3. Risk assessment of electricity price
3.1. Market clearing and nodal price
Firstly, the clearing model of electricity market is established considering the guaranteed consumption of renewable energy. The objective function is to minimize the sum of total power purchase cost, penalty cost for wind power abandonment (WPA), photovoltaic power abandonment (PPA) and load curtailment:

\[ \min \sum_{s=1}^{S} \sum_{j=1}^{J} \left( C_j \left( P_{G,s,j}^r \right) + r_r \left( W_{s,j}^{WPA} - W_{s,j}^r \right) + r_r \left( S_{s,j}^{SPP} - S_{s,j}^r \right) + r \left( P_{D,s,j}^r - \Delta P_{D,s,j}^r \right) \right) \]  

where \( P_{G,s,j}^r \) is the active power output of units at node \( j \) under scenario \( s \). \( C_j ( \cdot ) \) means the generation cost function of units at node \( j \), which is dependent on \( P_{G,s,j}^r \), \( W_{s,j}^{WPA} \) and \( S_{s,j}^{SPP} \) respectively refer to the forecast output of wind farm and photovoltaic power station at node \( j \) under scenario \( s \). \( W_{s,j}^r \) and \( S_{s,j}^r \)
mean the actual output of wind power plant (WPP) and photovoltaic power plant (PPP) at node \( j \) under scenario \( s \). \( P_{D,j}^s \) represents the active power load at node \( j \). \( \Delta P_{D,s,j}^r \) means the load curtailment of node \( j \) under scenario \( s \). \( r_w \), \( r_s \) and \( r \) are respectively the penalty prices for WPA, PPA and load curtailment. \( N_j \) and \( T \) are the number of nodes and transaction cycle.

Meanwhile, the following constraints are satisfied [2]:

1) Nodal power balance equation:

\[
P_{G,s,j}^r + W_{j}^r + S_{j}^r - P_{D,j}^s = \sum_{k=1}^{N} V_{j}^r (G_{j,k} \cos \theta_{s,j,k} + B_{j,k} \sin \theta_{s,j,k})
\]

(4)

\[
Q_{G,s,j}^r - Q_{D,j}^r = \sum_{k=1}^{N} V_{j}^r (G_{j,k} \sin \theta_{s,j,k} - B_{j,k} \cos \theta_{s,j,k})
\]

(5)

where \( Q_{G,s,j}^r \) is the reactive power output of units at node \( j \) under scenario \( s \). \( Q_{D,j}^r \) represents the reactive load at node \( j \). \( V_{j}^r \) refers to the voltage amplitude of node \( j \) under scenario \( s \). \( \theta_{s,j,k} \) is the voltage phase angle difference between node \( j \) and nodes \( k \) under scenario \( s \). \( G_{j,k} \) and \( B_{j,k} \) are respectively the real and imaginary parts of the elements in row \( j \) and column \( k \) of admittance matrix.

2) Output limits of units:

\[
P_{G,j}^{min} \leq P_{G,s,j}^r \leq P_{G,j}^{max}
\]

(6)

\[
Q_{G,j}^{min} \leq Q_{G,s,j}^r \leq Q_{G,j}^{max}
\]

(7)

\[
\Delta P_{G,j}^{max} \leq P_{G,s,j}^r - P_{G,s,j}^{pre} \leq \Delta P_{G,j}^{max}
\]

(8)

\[
0 \leq W_{j}^r \leq W_{j}^{max}
\]

(9)

\[
0 \leq S_{j}^r \leq S_{j}^{max}
\]

(10)

where \( P_{G,j}^{min} \) and \( P_{G,j}^{max} \) are respectively the lower limit and upper limit of active power output of unit at node \( j \). \( Q_{G,j}^{min} \) and \( Q_{G,j}^{max} \) are respectively the lower limit and upper limit of reactive power output of unit at node \( j \). \( \Delta P_{G,j}^{low} \) and \( \Delta P_{G,j}^{upp} \) are respectively the ramp down limit and ramp up limit of active power output of unit at node \( j \).

3) Transmission limit of lines:

\[
|F_{l}^r| \leq F_{l}^{max}
\]

(11)

where \( F_{l}^r \) the power flow through line \( l \) under scenario \( s \). \( F_{l}^{max} \) represents the transmission capacity of line \( l \).

4) Voltage limit:

\[
V_{j}^{min} \leq V_{j}^r \leq V_{j}^{max}
\]

(12)

where \( V_{j}^{min} \), \( V_{j}^{max} \) are respectively the lower limit and upper limit of voltage amplitude of node \( j \).

5) Load curtailment limit:

\[
0 \leq \Delta P_{D,s,j}^r \leq P_{D,j}^r
\]

(13)

The above electricity market clearing model as shown in equation (3)-(13) is a nonlinear optimization problem. The interior point method has the advantages of strong convergence and fast calculation speed in solving nonlinear optimization problems [7]. Therefore, the interior point method can be used to solve the above model and obtain the clearing results.
Based on the above electricity market clearing model, the Lagrange function $L_s$ can be obtained, which can be used to calculate the node active power price and node reactive power price [2]:

$$
\rho_{p,s,j} = \frac{\partial L_s}{\partial p_{D,s,j}} = \lambda_{p,s,j}
$$

(14)

$$
\rho_{q,s,j} = \frac{\partial L_s}{\partial q_{D,s,j}} = \lambda_{q,s,j}
$$

(15)

Furthermore, the average active power price and average reactive power price are calculated as

$$
\rho_{p,s} = \frac{\sum_{j=1}^{N_s} \rho_{p,s,j}}{N_e}
$$

(16)

$$
\rho_{q,s} = \frac{\sum_{j=1}^{N_s} \rho_{q,s,j}}{N_e}
$$

(17)

### 3.2. Price risk indexes

Due to the fluctuation and intermittence of REG output, the electricity price may be very high in several scenarios or fluctuate significantly in different scenarios, which may cause the risk of electricity price. Therefore, the risk indexes of electricity price are proposed. In addition, the active power price is studied in this paper, without special explanation, the risk index refers to the active power price.

1) Expected system price (ESP) $\bar{\rho}_p^t$: evaluating the expected level of system average electricity price under all possible scenarios.

$$
\bar{\rho}_p^t = \sum_{s=1}^{N_s} p_s \rho_{p,s}^t
$$

(18)

where $N_s$ is the number of scenarios. $p_s$ is the probability of scenario $s$.

2) Standard deviation of system price (SDSP) $\sigma_p^t$: evaluating the fluctuation of average electricity price in all possible scenarios.

$$
\sigma_p^t = \sqrt{\frac{\sum_{s=1}^{N_s} p_s (\rho_{p,s}^t - \bar{\rho}_p^t)^2}{N_s}}
$$

(19)

3) Probability of system peak price (PSPP) $\zeta_p^t$: evaluating the possibility of higher average electricity price in all possible scenarios.

$$
\zeta_p^t = \frac{\sum_{s=1}^{N_s} \sum_{t=1}^{T} \mathbb{1}(\rho_{p,s}^t > \rho_{p,wp}^t)}{T}
$$

(20)

where $\rho_{p,wp}^t$ is electricity price threshold.

### 4. Case study

#### 4.1. Data description

In order to validate the effectiveness of the proposed method, the modified IEEE30 bus system is utilized for case studies. The system consists of 6 conventional units, 30 nodes, and 41 lines. Load data, unit parameters, and bidding information can be found in [8], line capacity parameters are provided in [9]. A WPP and a PPP are connected at node 20 and node 28 respectively, and the generating capacity is set according to different analysis environments. Considering that the marginal generation cost of wind power and photovoltaic is very small, the bidding parameters are set to the lowest. The historical data
of wind power and photovoltaic refer to [10]. The penalty price for WPA and PPA is set as 1000 RMB/MW·h, and the penalty price for load shedding is set as 5000 RMB/MW·h. The electricity price threshold $\rho_{\text{cap}}$ is determined by the highest value of market clearing electricity price.

4.2. Calculation results
In order to study the impact of different renewable energy penetration on price risk, five analysis environments are set.

Environment 0 (E0): WPP capacity 0 MW, PPP capacity 0 MW;
Environment 1 (E1): WPP capacity 50 MW, PPP capacity 0 MW;
Environment 2 (E2): WPP capacity 0 MW, PPP capacity of 50 MW;
Environment 3 (E3): WPP capacity 50 MW, PPP capacity 50 MW;
Environment 4 (E4): WPP capacity 70 MW, PPP capacity 70 MW;
Environment 5 (E5): WPP capacity 100 MW, PPP capacity 100 MW.

Firstly, the risk index of electricity price in each environment is calculated. According to the historical data of wind power and photovoltaic, the scenario generation algorithm of REG output proposed in Section 2 is used to obtain the final 5 typical scenarios: wind power output, photovoltaic output and scenario probability, which are shown in figure 1. The real value of wind power and photovoltaic output can be converted according to the plant capacity set in each environment.

![Figure 1. Scenarios of wind power and photovoltaic power](image)

The calculation results of the ESP, SDSP, PSPP values under different analysis environments are shown in figure 2, table 1 and table 2 respectively. It can be seen from Fig. 1 that the overall electricity price level of the system decreases after the renewable energy is integrated into power grids, and the higher the renewable energy penetration rate is, the more obvious the electricity price decreases. This can be explained by the fact that the generation cost of renewable energy is lower than that of conventional units. With the increase of penetration rate, the output of REG is also increasing, replacing some high-cost units, so the ESP also decreases.

To investigated the fluctuation of electricity price caused by the uncertainty of renewable energy, the SDSP index values under different analysis environments are listed in table 1. It can be seen that the SDSP values under different renewable energy penetration rates are various. The higher the penetration rate, the greater the SDSP. Comparing E1 and E2, the SDSP in E1 is larger, indicating that wind power is more likely to lead to the fluctuation of electricity price than photovoltaic. This is because the standard deviation of forecasting error of wind power is larger than photovoltaic in this case study. In addition, the SDSP is relatively high in the period of 15h-20h, during which the REG output is at the peak, and the electricity price is more sensitive to the fluctuation of REG output.

Different from the SDSP, the relationship between PSPP and renewable energy penetration is the opposite. It can be seen from table 2 that with the increase of renewable energy penetration, the PSPP values gradually decrease. This is because the increase of REG leads to the overall decline of electricity price level, so the probability of peak electricity price is correspondingly reduced.
Table 1. The SDSP index values under different analysis environments in some periods

| Time/h | E1  | E2  | E3  | E3  | E4  | E5  |
|--------|-----|-----|-----|-----|-----|-----|
| 10     | 0.00| 0.00| 0.00| 0.00| 0.00| 0.95|
| 11     | 0.00| 0.00| 0.00| 0.00| 0.43| 0.89|
| 12     | 0.95| 0.00| 0.95| 0.95| 5.29| 0.00|
| 13     | 0.00| 0.00| 0.00| 0.00| 7.17| 0.00|
| 14     | 0.00| 0.00| 0.00| 0.00| 7.17| 0.00|
| 15     | 0.88| 0.00| 0.88| 0.88| 7.17| 27.54|
| 16     | 0.00| 7.89| 0.00| 0.00| 7.17| 27.54|
| 17     | 2.86| 0.00| 0.00| 0.00| 7.17| 0.95|
| 18     | 3.56| 0.00| 0.00| 0.00| 0.58| 0.88|
| 19     | 3.97| 0.00| 9.72| 9.72| 0.30| 9.77|
| 20     | 3.97| 1.41| 3.97| 3.97| 0.50| 9.72|

Table 2. The PSPP index values under different analysis environments

| Environment | $\zeta_\alpha$ |
|-------------|---------------|
| 1           | 21.64%        |
| 2           | 39.63%        |
| 3           | 8.48%         |
| 4           | 4.05%         |
| 5           | 3.30%         |

5. Conclusions
In this paper, a price risk assessment method considering guaranteed accommodation of renewable energy in electricity market is proposed. By taking the impact of the uncertainty of REG output on the clearing price into account, the evaluation indexes of price risk are constructed. The effectiveness of the method is validated by a modified IEEE 30 bus system. Results show that with the increase of renewable energy penetration, the expected electricity price level and the probability of peak electricity price can be reduced to a certain extent, but the fluctuation degree of electricity price may be increased. Especially in the peak period of REG output, the fluctuation of system electricity price is obvious, which may have high electricity price risk. As a result, while promoting the consumption of renewable energy, the price risk caused should also be paid attention to. These findings could provide guidance for the related research of renewable energy participating in the electricity market.

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