Flexible units planning and operational optimization model under large-scale wind power access

Jing Gou¹, Weiting Xu¹, Xinting Yang¹, Yunche Su¹, Zhibo Jin²,³, Hao Xu² and Huaqiang Li²

¹State Grid Sichuan Economic Research Institute;
²Intelligent Electric Power Grid Key Laboratory of Sichuan Province (Sichuan University), Chengdu 610065, China
³Email: jinzb@stu.scu.edu.cn

Abstract. After large-scale wind power access to the power grid, the requirements of flexibility of power system become higher, and it is necessary to transform the flexibility of the largest proportion of resources, the thermal units. Firstly, a mathematical model of flexibility requirements and supply of power system is established. Secondly, a supply and demand of flexibility matching probability model based on stochastic chance-constrained programming is built (CCP). Then, a flexible resource planning and operation optimization model is proposed aim to minimize the operational cost of the system. After the transformation of the model, it is solved by using the commercial solver CPLEX. Finally, an example is used to verify the validity of the model. The results show that after the transformation the thermal units can promote the consumption of wind power and reduce the total cost of planning and operation.

1. Introduction

In recent years, with the depletion of fossil energy and the increasing of environmental pollution, renewable and cleaner energy power generation represented by wind power has received extensive attention, and the proportion of grid connection has been increasing. However, due to the uncertainty of wind power output, there is a strong impact on the power balance of the system, resulting in a low proportion of the consumption of wind power. Therefore, it is necessary to increase the flexibility of the power system to achieve efficient consumption of wind power.

Most of the studies solve the problem of wind power access and consumption, but the investment cost is expensive and the project cycle is relatively long [1-3]. Among the existing resources of power system, conventional thermal units account for the largest proportion of capacity, which is potential to become the resources of flexibility. However, there are many problems in thermal units, such as high minimum technical output and slow climbing speed, which lead to the lack of flexibility of thermal units. Therefore, the flexibility reformation of thermal units is imperative. At present, some attempts to demonstrate the feasibility reformation of thermal units have been carried out [4-5]. On the other hand, based on the system investment and operational cost, a reformation planning model of thermal units considering the long-term dispatching of power system is proposed in the literature [6], and the optimal flexibility reformation and operation scheme of thermal units are worked out.

Based on the above, this paper focuses on the flexibility reformation of thermal units in high proportion wind power system. First of all, according to the randomness and fluctuating of the net load caused by wind power, a model considering flexibility supply and demand matching is set up based on
stochastic chance-constrained programming (CCP). Secondly, in order to achieve economic optimization, the units start and stop constraints, flexibility margin opportunity constraints are considered in the flexibility reformation planning and operation comprehensive stochastic optimization model of thermal units. Then, based on the stochastic programming theory and linear transformation, the model is transformed into a mixed integer linear programming model. The commercial optimization software is used to solve the problem, and the optimal reform scheme of thermal units, the optimal operation mode of thermal units in each scenario and the wind abandoning plan is obtained. Finally, the applicability and effectiveness of the proposed model are verified by an example.

2. Stochastic model of flexibility supply and demand matching based on CCP

2.1. Power system operational flexibility

Power system flexibility refers to the ability of power system to quickly and effectively allocate existing resources and match the random variation of load fluctuation and renewable energy output under a certain time scale to meet the power grid operation and economic constraints. The demand for operational flexibility of high proportion wind power system mainly comes from the fluctuation of net load and its prediction error.

\[
F^N(t) = \left[ P^{NL}(t+1) - P^{NL}(t) \right] \\
\quad + \left[ P^{NL}(t+1) - P^{NL}(t+1) \right] \\
\quad + \left[ P^{NL}(t) - P^{NL}(t) \right] \\
= P^{NL}(t+1) - P^{NL}(t) \\
P^{NL}(t) = L(t) - P^{w,r}(t) \\
= L(t) - (P^w(t) - P^{w,ab}(t) + e^w(t))
\] (1)

Where \( F^N(t) \) is the system flexibility requirement of time \( t \), which is a random variable. When \( F^N(t) > 0 \), there is an upward flexibility requirement, when \( F^N(t) < 0 \), there is a downward flexibility requirement. \( P^{NL}(t) \) is the actual value of the net load at time \( t \); \( P^{NL}(t) \) is the predicted value of the net load at time \( t \); \( L(t) \) is the load at time \( t \); \( P^w(t) \), \( P^{w,ab}(t) \) and \( P^{w,r}(t) \) are the predicted value, curtailed wind power and actual output of wind power at time \( t \), respectively; \( e^w(t) \) is the prediction error of wind power output at time \( t \). Since the distribution of wind power prediction error is not the focus of this paper, without losing the generality, considering that the wind power prediction error satisfies the normal distribution with a mean value of zero [7], in details:

\[
e^w(t) = P^{w,r}(t) - P^w(t) \\
e^w(t) \sim N(0, \delta(t)) \\
\delta(t) = \frac{1}{5} P^w(t) + \frac{1}{50} W_i
\] (3)

Where \( \delta \) is the standard deviation of normal distribution and \( W_i \) is the installed capacity of wind power.

The generalized power system flexibility resources are composed of adjustable units on the power side, controllable load on the load side and energy storage devices. However, considering that the promotion of demand-side response technology and large-scale energy storage technology has not yet met the requirements to be stable flexibility supply in China, and demand-side response is often considered as a strategy in the optimal operation of distribution network, it is rarely involved in the planning problem. Therefore, this paper focuses on the upward and downward flexibility provided by adjustable thermal units to deal with the random change of net load, so as to ensure the safe and stable operation of power system. The upward and downward flexibility supply of the system at time \( t \) is represented by \( F^{S,up}(t) \) and \( F^{S,down}(t) \), respectively. For specific flexibility modeling of adjustable units, see section 3.2.3.
Based on the above analysis, the flexibility margin index is constructed to evaluate the flexibility supply and demand matching degree of the system.

\[ F_{\text{up}}(t) = F^{S,\text{up}}(t) - F^N(t) \]
\[ F_{\text{down}}(t) = F^{S,\text{down}}(t) + F^N(t) \]

(4)

Where \( F_{\text{up}}(t) \) and \( F_{\text{down}}(t) \) denote the upward and downward flexibility margin at time \( t \), respectively.

Only when \( F_{\text{up}}(t) \geq 0 \) and \( F_{\text{down}}(t) \geq 0 \), the flexibility of the system in period \([t, t+1]\) is abundant.

2.2. Stochastic model of flexibility supply and demand matching based on CCP

As described in Section 1.1, the flexibility margin of the system is a random variable, so it is feasible to describe it by opportunity constraints, which means that the probability of flexibility of the system can meet a given confidence level.

\[ \Pr\{F_{\text{up}}(t) \geq 0\} \geq \beta_{\text{up}}(t) \]
\[ \Pr\{F_{\text{down}}(t) \geq 0\} \geq \beta_{\text{down}}(t) \]

(5)

Where \( \beta_{\text{down}}(t) \) and \( \beta_{\text{up}}(t) \) are the confidence levels that the upward and downward flexibility margin opportunity should be satisfied. When the probability that the flexibility supply exceeds the requirement is greater than the given confidence level, it can be said that the flexibility of supply and demand matches under the current system requirements.

3. Stochastic optimization model for flexibility reformation of thermal units considering start and stop

The purpose of the reformation of thermal units planning model constructed in this paper is to carry out flexibility reformation of the existing thermal units in order to meet the needs of power grid with high proportion wind power in the future. And a reasonable start and stop scheme of the units, a reasonable wind curtailment plan and the sufficient flexibility supply in the system are the basis to ensure the safe and reliable operation of the power system. Hence, the time series of change of units operating state along with the fluctuation of wind power and load is considered. In addition, the uncertainty of wind power prediction, the constraint on system operation flexibility margin are also considered in this paper. The problem of investment and reformation of thermal units and the problem of operation and dispatching are jointly optimized.

3.1. Objective functions

With the goal of optimizing the annual comprehensive cost \( C_{\text{total}} \), the objective functions are composed of thermal units reform cost \( C_{\text{rebuild}} \), operation cost \( C_{\text{op}} \), flexibility supply cost \( C_F \), wind curtailment cost \( C_{ab} \), the details are as follows:

\[ \min C_{\text{total}} = C_{\text{rebuild}} + C_{\text{op}} + C_F + C_{ab} \]

(6)

\[ C_{\text{rebuild}} = \frac{\alpha(1 + \alpha)^n}{(1 + \alpha)^n - 1} \sum \mathcal{C}_i \]

(7)

\[ C_{\text{op}} = D \sum_{m \in M} \mathcal{Pr}(m) \sum_{i=1}^{T} \left[ \sum_{t \in \Omega_i} \left( f_i(P_{i,m}^n(t)) + SU_i z_{i,m}^u(t) + SD_i z_{i,m}^d(t) \right) + c^n(P_{i,m}(t) - P_{i,m}^{\text{w,ab}}(t)) \right] \]

(8)

\[ C_F = D \sum_{m \in M} \mathcal{Pr}(m) \sum_{i=1}^{T} \sum_{t \in \Omega_i} \left[ c_{i,m}^{\text{up}} F_{i,m}^{S,\text{up}}(t) + c_{i,m}^{\text{down}} F_{i,m}^{S,\text{down}}(t) \right] \]

(9)
Where $\Omega_g$ is the collection of thermal units, $\alpha(1+\alpha)^n$ is the fund recovery coefficient, which is used to converse one-time reformation investment to annual investment fee; $\alpha$ is the sum of discount rate and inflation rate, taken as 0.1; $n$ is the economic and applicable life of the project, taken as 20; $c_i^{\text{rebuild}}$ is the one-time investment cost for the reformation of thermal units; $x_i$ is the 0-1 variable indicates whether the thermal units should be reformed or not; $D$ is the number of days included in the current year; $M$ is the set of wind power output scenarios considered in the model; $\Pr(m)$ is the probability of scene $m$; $T$ is the number of periods considered in single scene; $P_m^{\text{ab}}(t)$ and $P_m^{\text{a}}(t)$ are the output of unit $i$ and wind power at time $t$ of scene $m$, respectively. The following is a concise description that no longer describes the subscript meaning of a variable with a subscript $m$.

3.2. Constraints

To ensure that the results of reformation of thermal units not only meet the power balance constraints of the system but can also deal with the sharp fluctuation \cite{8}. Therefore, there are the power balance constraints, units operation constraints and system flexibility margin constraints of various operating scenarios should be met in the model.

3.2.1. System power balance constraint. The power balance constraint of the system is shown in formula (11) to ensure that the generating power of each scene and each period meets the load demand.

$$C_{\text{ab}} = D \sum_{m \in M} \Pr(m) \sum_{t=1}^{T} c_{\text{wab}} P_m^{\text{wab}}(t)$$

(10)

Where $\Omega_g$ is the collection of thermal units, $\alpha(1+\alpha)^n$ is the fund recovery coefficient, which is used to converse one-time reformation investment to annual investment fee; $\alpha$ is the sum of discount rate and inflation rate, taken as 0.1; $n$ is the economic and applicable life of the project, taken as 20; $c_i^{\text{rebuild}}$ is the one-time investment cost for the reformation of thermal units; $x_i$ is the 0-1 variable indicates whether the thermal units should be reformed or not; $D$ is the number of days included in the current year; $M$ is the set of wind power output scenarios considered in the model; $\Pr(m)$ is the probability of scene $m$; $T$ is the number of periods considered in single scene; $P_m^{\text{ab}}(t)$ and $P_m^{\text{a}}(t)$ are the output of unit $i$ and wind power at time $t$ of scene $m$, respectively. The following is a concise description that no longer describes the subscript meaning of a variable with a subscript $m$.

3.2.2. Conventional constraint of thermal units. Constraints of thermal units include maximum and minimum output constraints, climbing constraints, minimum units start and stop time constraints.

1) maximum and minimum output constraints

This constraint ensures that the output of the thermal units is between the minimum technical output and rated output. After the flexibility reformation of the units, the minimum technical output is reduced, and the effective output range of the units is expanded correspondingly.

$$[1-x_i]P_{i,\text{min}}^{\text{r}} + x_i P_{i,\text{min}}^{\text{m}} \leq \nu_{i,m}(t) \leq P_{i,\text{max}}^{\text{r}}$$

(12)

Where $P_{i,\text{max}}^{\text{r}}$ and $P_{i,\text{min}}^{\text{r}}$ are the rated output and minimum technical output of the unit $i$ before reformed; $\overline{P_{i,\text{min}}^{\text{m}}}$ is the minimum technical output of the unit $i$ after reformed.

2) Climbing constraints of thermal units
The constraints ensure that the change of output of thermal units in adjacent period should be less than the maximum climbing capacity

\[
\begin{align*}
P_{i,m}^h(t) - P_{i,m}^h(t-1) &\leq \nu_{i,m}(t-1)R_t + x_i(\hat{R_t} - R_t) \\
+ (\nu_{i,m}(t-1) - \nu_{i,m}(t))R_{i,\text{start}} + (1 - \nu_{i,m}(t))P_{i,\text{max}}
\end{align*}
\]

(13)

\[
\begin{align*}
P_{i,m}^h(t-1) - P_{i,m}^h(t) &\leq \nu_{i,m}(t)R_t + x_i(\hat{R_t} - R_t) \\
+ (\nu_{i,m}(t) - \nu_{i,m}(t-1))R_{i,\text{start}} + (1 - \nu_{i,m}(t-1))P_{i,\text{max}}
\end{align*}
\]

(14)

Where \(R_t\) and \(\hat{R_t}\) are the maximum climbing power before and after the reformation; \(R_{i,\text{start}}\) and \(R_{i,\text{shut}}\) are start-up and shutdown climbing power, respectively.

3) Constraints on start-up and shutdown time of units

In order to take into account the effect of flexible start and stop of the units on promoting the consumption of wind power, the start and stop state of the units is taken as the decision variable and constrained.

\[
\begin{align*}
\sum_{n=TU_j}^{\infty} z_m^\text{su}(t) &\leq \nu_{i,m}(t) & t \geq TU_j + 1 \\
\sum_{n=-TD_j}^{\infty} z_m^\text{sd}(t) &\leq 1 - \nu_{i,m}(t) & t \geq TD_j + 1
\end{align*}
\]

(15)

Where \(TU_j\) and \(TD_j\) are the minimum running time and downtime of thermal units, respectively.

3.2.3. Constraint on system operation flexibility

1) Constraints on flexibility supply

The upward and downward flexibility of the system are mainly provided by the adjustable units, and are limited by the climbing rate of the units and the upward and downward limit of the output of the units.

\[
\begin{align*}
F_{i,m}^\text{up}(t) &= \sum_{i} F_{i,m}^\text{up}(t) \\
F_{i,m}^\text{down}(t) &= \sum_{i} F_{i,m}^\text{down}(t)
\end{align*}
\]

(16)

\[
\begin{align*}
F_{i,m}^\text{up}(t) &\leq \min((1 - x_i)R_t + x_i\hat{R_t} - P_{i,\text{max}} - P_{i,m}^h(t)) \\
F_{i,m}^\text{down}(t) &\leq \min((1 - x_i)R_t + x_i\hat{R_t} - P_{i,\text{max}}(t) - (1 - x_i)P_{i,\text{max}} - x_iP_{i,m}^h)
\end{align*}
\]

It can be seen from formula (16) that when \(x_i=1\), the value range of \(F_{i,m}^\text{up}(t)\) and \(F_{i,m}^\text{down}(t)\) is extended, which indicates that the flexibility supply of thermal units is improved after the flexibility reformation.

2) Constraints on flexibility margin

By adding the scene variable to formula (5), the opportunity constraint of system flexibility margin is obtained. The idea is the same as formula (5), that is, to ensure the system flexibility supply and demand matching to meet the confidence requirements at all times in each scene. Combined with (1-3) and (11), the constraints on flexibility margin can be obtained as follows:

\[
\begin{align*}
\Pr\left[F_{a}^\text{up}(t) - F_{a}^\text{down}(t) \geq 0 \right] &\geq \beta^\text{up}(t) \\
\Pr\left[F_{a}^\text{up}(t) + F_{a}^\text{down}(t) \geq 0 \right] &\geq \beta^\text{down}(t) \\
F_{a}^\text{up}(t) &= \sum_{i} P_{i}^\text{up}(t) + \sum_{i} P_{i}^\text{up}(t) - c_i'(t + 1) + c_i'(t) \\
[c_i'(t + 1) - c_i'(t)] - N(0, \sqrt{\sigma_i^2(t) + \delta_i^2(t + 1)}) &\leq \Delta F_{a}^\text{up}(t) \geq 0, \Delta F_{a}^\text{down}(t) \geq 0
\end{align*}
\]

(17)
Where \( \sqrt{\sigma^2(t) + \sigma^2(t+1)} \) is the standard deviation of the normal distribution of flexibility demand. In this paper, the normal distribution of wind power prediction error before and after is considered to be independent.

4. Model transformation and solution

4.1. Model transformation

The model established in this paper is a mixed integer nonlinear stochastic programming model with high dimension and large scale. In order to improve the efficiency of solving the model, it is necessary to carry out deterministic equivalence and linearization of the model.

4.1.1. Transformation of opportunity constraints. Literature [9] points out that if the random variable in the opportunity constraint can be converted to one side of the inequality, the original CCP random constraint can be transformed into a deterministic constraint. In addition, formula (18) is a linear constraint,

\[
\sum_{i \in \Omega t} P_{i,m}^h(t+1) - \sum_{i \in \Omega t} P_{i,m}^l(t) - \sum_{i \in \Omega t} F_{i,m}^{\text{up}}(t) - \phi(1-\beta^p(t)) \leq 0
\]  

\[
-\sum_{i \in \Omega t} P_{i,m}^h(t+1) + \sum_{i \in \Omega t} P_{i,m}^l(t) - \sum_{i \in \Omega t} F_{i,m}^{\text{down}}(t) - \phi(1-\beta^d(t)) \leq 0
\]

Where \( \phi \) is the cumulative probability distribution function of random variables \( e^w(t+1) - e^w(t) \);

4.1.2. Piecewise linearization of generation cost. The coal consumption cost of thermal units is linearized by piecewise linearization method, the formula (10) is transformed into a linearized model, the specific methods are referred to literature [10].

4.1.3. Transformation of output constraint of thermal units. So far, the whole model is transformed into a mixed integer linear programming problem by using the big M methods[11] for formula (13).

\[
\begin{align*}
P_{i,m}^h(t) &\geq [\nu_{i,m}(t)P_{i,max}^h + x(t)(P_{i,max}^l - P_{i,min}^l)] \\
P_{i,m}^l(t) &\leq \nu_{i,m}(t)P_{i,max}^l \\
P_{i,m}^h(t) &\geq 0
\end{align*}
\]

4.2. Solution

Based on the YALMIP toolkit configured on the MATLAB2016a platform, the CPLEX commercial solver is called to solve the mixed integer linear programming problem. Among them, MATLAB is responsible for the transformation of the model and the analysis and display of the results; YALMIP is responsible for the establishment of the model and the call and solution of CPLEX.

5. Example analysis

5.1. Example illustration

In order to verify the effectiveness and applicability of the model, and analyze the influence of thermal units flexibility reformation on units operation, flexibility supply and demand matching, and the consumption of wind power, the example system in literature [6] is used to carry out simulation optimization.

Load and wind power data are measured by BPA (Bonneville Power Administration) in 2018 [12], and is scaled to a certain extent in order to adapt to the example system in this paper. Furthermore, the wind power and load power curves of typical wind power scene are obtained by K-means clustering. The installed capacity of wind power is 1000MW, accounting for 50% of the peak load (2000MW),
which means that the system belongs to a high proportion of wind power access system. \( \beta^\text{up}(t) \) and \( \beta^\text{down}(t) \) in the wind power scenario are set to 0.95 and 0.85, respectively.

5.2. Results and analysis of numerical examples

The optimal reformation scheme of thermal units solved by the model established in this paper is shown in Table 1. Unit 4 and unit 5 need to be reformed, and the cost composition of the reformation case is shown in Table 1. In order to further quantitatively analyze the influence of the flexibility reformation of thermal units on the operation of the system, the applicability of the model is verified by the comparison the optimization results before and after the reformation.

Table 1 shows that it is more economical after the reformation. This is because after the flexibility reformation of the units, the system can provide more flexibility supply, reduce the mismatch between supply and demand, the risk cost of wind power curtailment cost is significantly reduced. The results show that the annual curtailed wind power of the modified scheme ② is \( 4.023 \times 10^5 \) MW, and the annual wind curtailment rate is 11.74%, which is significantly lower than that of 11.1043 \( \times 10^6 \) MW and 39.44% of scheme ①. In addition, after the flexibility reformation of thermal units, units start-up and shutdown caused by units output constraint and climbing rate constraint is reduced, so the start and stop cost is also reduced by 38.02%. Although there is a certain increase in the flexibility call cost and annual operating cost of scheme ② compared with scheme ①, the total cost of scheme ② is still reduced by 1.39%.

Table 1. Cost analysis of different thermal reformation schemes\(^{a,b}\).

| Reformation schemes | Total cost | Operating cost | Cost of reformation | Cost of curtailed wind power | Flexibility source calling cost | Start and stop cost | Wind curtailment rate |
|---------------------|------------|----------------|---------------------|-----------------------------|-------------------------------|---------------------|----------------------|
| ①Original          | 18.6697    | 15.8728        | 0                   | 1.1043                      | 1.6663                        | 0.0263              | 39.44%               |
| ②Units /4/5        | 18.4087    | 16.0797        | 0.2232              | 0.4023                      | 1.6835                        | 0.0200              | 14.37%               |

\(^{a}\) The data listed in the table are annual average data  
\(^{b}\) The units of the cost in the table is 100 million CNY.

In order to further analyze the influence of units flexibility reformation on system operation, two wind power scenarios among 19 scenarios are selected to compare the optimal operation status of the system before and after the reformation. The results are shown in Figure 1 and Figure 2.

Figure 1 shows the result of 24-hour optimal operation of the system in the first selected scenario. At period 1-15, the output of thermal units of scheme ② is lower than that of scheme ①, and the actual output wind power of scheme ② is higher than that of scheme ①. At period 16-24, the thermal power and wind power output of the two schemes are the same, because the wind power output of the two schemes is low during this period, and the wind power output of the two schemes is fully absorbed.

In addition, the constraint on flexibility margin of scheme ① did not meet the given confidence level in the periods 4-5 and 11-13, while the flexibility of scheme ② was insufficient only at the time 13. It should be noted that because the upward flexibility is given priority to the downward flexibility, there is no lack of upward flexibility in each period of the scenario. Figure 1 (b) shows the 24-hour optimization results under the daily output scenario of wind power. It can be seen that after the flexibility reformation of thermal units, the consumption of wind power and the matching of flexible supply and demand have been significantly improved, which is not to be described in detail.

Figure 2 shows the optimized output curve of some units before and after the reformation of thermal units in two scenarios. Under the first selected scenario, four units (unit 1, 3, 4 and 5) were involved in the operation before the reformation, of which unit 3 shut down at 16:00 due to the decrease of net load while after the reformation, unit 3 is always out of line, only unit 1, 4, 5 participate in the operation, and the three units did not stop at 16:00. Under the second selected
scenario, the first five units are all involved in the operation, of which unit 2 is started and stopped respectively at 4:00 and 23:00 due to the fluctuation of net load; after the transformation, only three units (unit 2, 4, 5) are involved in the operation, and they are always online. It shows that after the flexibility reformation of the units, the behavior of start and stop is less, and the start and stop cost is reduced to a certain extent.

![Figure 1](image1.png)

**Figure 1.** Optimization results of system operation in different thermal reformation schemes.

![Figure 2](image2.png)

**Figure 2.** Units output of different thermal reformation schemes.

According to the above analysis, the flexibility transformation of thermal units is of great practical significance to promote the consumption of wind power, ensure the matching of supply and demand of system flexibility, and optimize the operation of thermal units.

6. Conclusions

Under the background of high proportion wind connected to the power grid, the random and fluctuating characteristics of wind power output put forward higher requirements for the flexibility of thermal units and seriously affect the planning and operation of power system. Therefore, in order to solve the problem of flexibility reformation of thermal units, a comprehensive stochastic optimization
model for flexibility reformation planning and operation of thermal units is established based on CCP. The effects of units start and stop optimization along with the constraints on operation flexibility margin are comprehensively considered, and the following conclusions are obtained through the comparative analysis of numerical example:

The reasonable flexibility reformation of thermal units cannot only improve the economy of system operation, but also promote the consumption of wind power, ensure the matching of supply and demand of system flexibility, and optimize the operating state of thermal units.

References

[1] Xiaowei D, Guiping Z, Yanzhang L 2017 Research on Battery Storage Sizing for Wind Farm Considering Forecast Error[J] Power System Technology 41(02) 103-108 (in Chinese)

[2] Wenfei Y, Yiwei Z, Bo Z, Yongzhang H 2018 Robust Optimization Allocation for Multi-Type Incentive-Based Demand Response Collaboration to Balance Renewable Energy Fluctuations[J] Transactions of China Electrotechnical Society 33(23) 155-168 (in Chinese)

[3] Song X, Zhijie W, Rui H, Ming Z, Yuejin W 2013 A Secure and Economic Planning Model for Fast Response Thermal Units Considering Grid-Integration of Large-Scale Wind Farm[J] Power System Technology 37(10) 2888-2895 (in Chinese)

[4] Zhang Jiquan, Zhang Yanbo, Su Lin 2016 Research on Feasible Solutions of Improving the Thermal Power Flexibility[J] Technology innovation and Application 31 201-201 (in Chinese)

[5] Yancan J, Tongtian D, Ying Z, Lihua C, Yong L 2015 Analysis on Economic Operation Mode of 600MW Fossil-fired Generating during Peak Shaving Low Load Operation[J] Turbine Technology 57(01) 61-64 (in Chinese)

[6] Xingmei L, Zhiming Z, Jie Y 2019 Flexibility Reformation Planning of Thermal units with Large-scale Integration of Wind Power[J] Automation of Electric Power Systems 43(03) 69-76 (in Chinese)

[7] Kamath C 2011 Associating weather conditions with ramp events in wind power generation[C] Power Systems Conference & Exposition, IEEE

[8] Ortega-Vazquez M A, Kirschen D S 2009 Estimating the Spinning Reserve Requirements in Systems With Significant Wind Power Generation Penetration[J] IEEE Transactions on Power Systems 24(1) 114-124

[9] Baodian L, Ruiqing Z, Gang W 2003 Uncertain planning and Application [M] Tsinghua University Press (in Chinese)

[10] Carrion M, Arroyo J M 2006 A computationally efficient mixed-integer linear formulation for the thermal units commitment problem[J] IEEE Transactions on Power Systems 21(3) 0-1378

[11] Jianchen L, Shanlin L 2018 Optimal Distributed Generation Allocation in Distribution Network Based on Second Order Conic Relaxation and Big-M Method[J] Power System Technology 42(08) 2604-2611

[12] Bonneville Power Administration 2018 Wind Generation & Total Load in The BPA Balancing Authority[EB/OL]