Optimization Methods of Renewable Integration in Power Market

Qihang Huang, Xiuli Wang and Yuchao Zhu

ABSTRACT

With utilization of large-scale renewable energy, renewable integration faces great challenges. In order to enhance power system’s ability to accommodate new energy and reduce electricity curtailment, an effective simulation optimization method on renewable integration is presented. Considering the constraints of transmission line capacities, an optimization model of renewable integration based on the calculation of electricity curtailment in peak regulation is set up. The measures to promote new energy accommodation in power market are proposed, including the increase of peak regulation depth, spinning reserve optimization, generation rights trade, and time-of-use (TOU) power price. Taking the actual power system of a province in 2018 as an example, the calculation and analysis of the typical scene were carried out, and effectiveness of the proposed method was proved.

Keywords: Electricity curtailment, power market, new energy accommodation.

INTRODUCTION

There are technical obstacles in large-scale renewable integration nowadays, and the phenomenon of hydropower/wind power/photovoltaic (PV) power curtailment are worsening [1-3]. There have been a few studies on renewable integration in power market [4-7]. Senlin Zhang [4] demonstrated the relationship between power market and energy conservation and emissions reduction, analyzing benefits of four bilateral trading patterns. Yanzhang Sun [5] designed the auxiliary service cost compensation mechanism from five aspects. On this basis, the new energy accommodation is analyzed, and corresponding policy development suggestions are put forward. Haoyong Chen [6] researched on how to combine energy-saving power generation dispatching in power market with market mechanism, proposed bidding transaction algorithm and designed a transaction mode. Guannan He [7] developed a model on the offering strategy optimization in day-ahead energy, reserve and regulation markets, which is robust for market price uncertainty and solar energy uncertainty. However, the impact of the power market on new energy has not been studied quantitatively. Based on the calculation of electricity curtailment in peak regulation [8, 9], this paper optimizes the method on renewable integration.
OPTIMIZATION MODEL OF RENEWABLE INTEGRATION

Optimization operation of renewable integration needs to satisfy the requirements of system load, reserve capacity and operating technical constraints of the units. Considering the volatility of renewable energy, optimization operation of renewable integration determines the state of each unit and load distribution among the units in order to minimize the total system operation cost for some expected periods in the future. The rational operation scheme of renewable integration can save energy, prolong the service lives of the units and bring great economic benefits.

Objective Function

The objective function of the model of renewable integration is

$$\min \sum_{i=1}^{G_c} \sum_{t=1}^{T} f(P_{C,i,t,s}^c) + \rho_L \sum_{t=1}^{T} u_{i,t,s} + \rho_R \sum_{t=1}^{T} v_{i,t,s} + \rho_U \sum_{i=1}^{G_c} \sum_{t=1}^{T} U_{i,t,s} + \rho_D \sum_{i=1}^{G_c} \sum_{t=1}^{T} D_{i,t,s}$$  \hspace{1cm} (1)

where $T$ is the number of hours in a day, that is 24. $G_c$ is the number of thermal power units in power system. The first item of the objective function is thermal power cost, $f$ is a function of variable fee of thermal power, $P_{C,i,t,s}^c$ is the power generation of the thermal power unit $i$ in hour $t$, $\rho_L$, $\rho_R$ denote penalty for loss of load and reserve, $\rho_U$, $\rho_D$ denote, start-up costs and shut-down costs of thermal power units, respectively. $u_{i,t,s}$, $v_{i,t,s}$ denote, the loss of load and reserve in hour $t$, respectively. $U_{i,t,s}$ denotes the start-up state of thermal power unit $i$ on day $t$, where 1 for the unit being started up while 0 for not. $D_{i,t,s}$ denotes the shut-down state of thermal power unit $i$ on day $t$, where 1 for the unit being shut down while 0 for not.

The objective function optimizes the mathematical expectation of generation cost as well as the state costs of the thermal power units in the scene $s$, and all the variables associated with the cost are attributable to coal consumption. Hydropower and intermittent power do not consume coal, so in order to minimize coal consumption, hydropower and intermittent power should be accepted as much as possible.

Constraints

1) Power Balance Constraints Considering Grid

$$\sum_{i=1}^{G_c} P_{C,i,t,s}^c + \sum_{i=1}^{G_c} P_{H,i,t,s}^H + \sum_{i=1}^{L_c} P_{L,in}^L + \sum_{i=1}^{L_c} P_{L,out}^L = D_t, \forall t, s \in S$$ \hspace{1cm} (2)

Where $P_{C,i,t,s}^c$, $P_{H,i,t,s}^H$ denote the power generation of the intermittent power unit $i$ and hydropower unit $i$ in hour $t$, respectively. $D_t$ denotes the load in hour $t$. $P_{L,in}^L$, $P_{L,out}^L$ denote the power in and out of the node from line $i$, respectively.

2) Thermal Power Output Constraints

$$P_{C,i,max}^c L_{i,t,s} \leq P_{C,i,t,s}^c \leq P_{C,i,\text{min}}^c, \forall i, t, s \in S$$ \hspace{1cm} (3)

Where $L_{i,t,s}$ denotes the state of the thermal power unit $i$ on day $t$, 0 for down, 1 for on. $P_{C,i,max}^c$ and $P_{C,i,\text{min}}^c$ denote the rate power and minimal technical output of thermal power unit $i$, respectively.

3) Minimum Startup Time Constraint

$$\sum_{i=1}^{G_c} \sum_{t=1}^{T} I_{i,t,s} \geq T_{i,\text{on}}, \forall i, n = 1, 2, ... T - T_{i,\text{on}} + 1$$ \hspace{1cm} (4)

Where $T_{i,\text{on}}$ denotes minimum running time of thermal unit $i$.  

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4) Minimum Shutdown Time Constraint
\[ \sum_{j=1}^{nT_{i,m}} I_{i,j} \leq T_{i,m} (1 - D_{i,j}), \forall i,n = 1,2,...T^* - T_{i,m} + 1 \] (5)

5) Start State Constraint
\[ I_{i,t} - I_{i,t-1} \leq U_{i,j}, \forall i,t = 1,2,...T^* \] (6)

6) Shutdown State Constraint
\[ I_{i,t} - I_{i,t-1} \leq D_{i,t}, \forall i,t = 1,2,...T^* \] (7)

7) Running State Constraint
\[ I_{i,t} - I_{i,t-1} = U_{i,j} - D_{i,t}, \forall i,t = 1,2,...T^* \] (8)

8) Intermittent Power Output Constraints
\[ 0 \leq P_{i,s,t}^w \leq w_{i,s,t}, \forall i,t,s \in S \] (9)

Where \( w_{i,t,s} \) denotes the maximum supply of intermittent power unit \( i \) in hour \( t \).

9) Hydropower Constraint
\[ \sum_{i=1}^{T_{i,m}} P_{i,s,t}^H \leq \text{Hydro}_i, \forall i,s \in S \] (10)

Where \( \text{Hydro}_i \) denotes the total generating capacity of hydropower plant \( i \) during the simulation time.

10) Spinning Reserve Constraint
\[ \sum_{i=1}^{T_{i,m}} P_{i,s,t}^H + \sum_{i=1}^{T_{i,m}} P_{i,s,t}^H + V_{i,s} \geq D_i + R, \forall i \] (11)

Where \( P_{i,s,t}^H \) denotes expected output of hydropower plant \( i \), \( R \) denotes spinning reserve.

11) Line Power Constraint
\[ -P_{i,s,t}^{\text{max}} \leq P_{i,s,t}^L \leq P_{i,s,t}^{\text{max}}, \quad -P_{i,s,t}^{\text{max}} \leq P_{i,s,t}^{\text{max}} \leq P_{i,s,t}^{\text{max}} \] (12)

Where \( P_{i,s,t}^{\text{max}} \) denotes the transmission capacity of line \( i \).

12) DC Power Flow Equation
\[ P_{ij} = B_{ij} (\theta_i - \theta_j) \] (13)

Where \( P_{ij} \) denotes power flow from node \( i \) to node \( j \), \( B_{ij} \) denotes the branch susceptance between node \( i \) and node \( j \), \( \theta_i \) denotes the phase angle of node \( i \).

### Electricity Curtailment Rate in Peak Regulation

Electricity curtailment rate in peak regulation is an important basis for evaluating the new energy accommodation ability in power system. This paper sets the calculation time scale of electricity curtailment rate in peak regulation at hour level. The new energy accommodation electricity of the day is calculated as (14).

\[ q_{\text{accept}} = \sum_{i=1}^{T_{i,m}} \sum_{s=1}^{T_{i,s}} P_{i,s,t}^w \] (14)

The new energy supply electricity of the day is calculated as (15).

\[ q_{\text{available}} = \sum_{i=1}^{T_{i,m}} \sum_{s=1}^{T_{i,s}} w_{i,s,t} \] (15)

Therefore, electricity curtailment rate of the day can be calculated as (16).

\[ \eta = (1 - q_{\text{accept}} / q_{\text{available}}) \times 100\% \] (16)
MEASURES TO PROMOTE NEW ENERGY ACCOMMODATION IN POWER MARKET

This paper proposes the following measures to promote new energy accommodation in power market. First is to increase the depth of peak regulation in the local power grid. Second is to optimize the spinning reserve of power system based on new energy output assurance to increase the accommodation space for new energy [10-12]. Third is generation rights trade, where small thermal power units sell some generating capacity to new energy units or large thermal power units. Last is to use TOU power price to adjust the load curve.

Increase of Peak Regulation Depth

For the problem of insufficient peak regulation capacity, the method of deep participation in peak regulation can be used. Deep participation in peak regulation means the thermal power units reduce their outputs more than usual while new energy units increase their outputs, in order to increase the system's ability to accommodate new energy. In general, the unit that has large capacity and good performance has the potential of deep participation in peak regulation. However, deep participation in peak regulation needs the thermal power unit to make a wide range of changes, so its service life and working efficiency will be affected. The peak regulation capacity of the system is determined by the minimum technical outputs of the conventional units. So the minimum technical outputs of the conventional units can be reduced in the model to increase capacity of peak regulation in the local power grid.

Spinning Reserve Optimization

Considering the probability that wind speed is above a certain value, the wind power output under a certain confidence level can be used as part of spinning reserve, so the spinning reserve can be reduced and the wind or solar electricity curtailment can be reduced. When the probability distribution of the total prediction error in the system is known, a certain confidence level can be set, then the spinning reserve capacity which meets the confidence level can be set with a deterministic method [13]. The model is changed in that certain spinning reserve is reduced.

Generation Rights Trade

Generation right trading mechanism allows those units who have high generating cost and large carbon emission to sell part or all of their scheduled contract energy to units of low generating cost and low carbon emission, so as to achieve the purpose of energy saving and emission reduction. Generation rights trade can be plants purchasing generation rights from other plants in the same enterprise, or trading between different power generating enterprises. New energy generation rights trade is in the direction of new energy plants or large thermal power units purchasing generation rights from small thermal power units, so the small thermal power units need to be shut down. The model is changed in that part of small thermal power units whose capacity are less than 50MW keep shutdown.

TOU Power Price

TOU power price belongs to price-based demand response. The price-based demand response refers to consumers response to the electricity retail price changes and adjust their demand for electricity accordingly, including TOU power price, real-time power price and
peak power price. TOU power price is the most representative way of demand response. The model is changed in that the load curve is altered [14]. The load after responding to the electricity price can be described as

\[
d_i = d_0^i \left[1 + E(t, t') \frac{\Delta p_t}{p_0^t} + \sum_{h=1}^{16} E(t, h) \frac{\Delta p_h}{p_0^h}\right]
\]

where \(E\) denotes the price elasticity matrix of demand, \(d_0^i\) denotes the original load in hour \(t\), \(p_0^i\) denotes the original electricity price in hour \(t\), \(\Delta p_t\) denotes the relative increment of the original electricity price in hour \(t\).

NUMERICAL ANALYSIS

Taking the typical scene of a province in the winter of 2018 as an example, this paper firstly analyzes the system characteristics, and then analyzes the situation of new energy electricity curtailment and system operation, finally analyzes the influence of the measures in power market on new energy accommodation.

System Characteristic Analysis

There were 69 thermal power plants, 8 hydropower plants, 4 PV power stations, 17 wind farms, a total of 160 thermal power units (including 20 combined heat and power generation units), 26 hydropower units, 60 wind power units, and 13 PV power units. The structure of the power source in power system is shown in Table I. The wind power and PV power curves are shown in Figure 1. The total system load is shown in Figure 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>thermal power</th>
<th>Hydropower</th>
<th>Wind Power</th>
<th>PV power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed Capacity</td>
<td>30037</td>
<td>1790.05</td>
<td>3654.8</td>
<td>4232.3</td>
</tr>
</tbody>
</table>

Figure 1. Wind Power Curve and PV Power Curve for Winter in 2018.
Renewable Integration Optimization Analysis

After simulation for the winter typical scene, it can be obtained that wind electricity curtailment rate for all day is 16.01%, while PV electricity curtailment rate is 10.76%. New energy electricity curtailment rate is 13.54%, and new energy accommodation electricity is 33050.37 MWh. Outputs for different types of energy in every hour of the typical day are shown in Figure 3. Output proportions of different types of energy are shown in Figure 4.

As is shown in Figure 3, the thermal power fluctuates with load fluctuation, output reduction of the units is required in the early morning and noon, and the unit outputs need to be increased in the forenoon and at night. The regulating effect of hydropower between 17 and 22 pm is obvious. As is shown in Figure 4, thermal power units play a supporting role in the process of new energy accommodation, accounting for 91%. The penetration rates of wind power, PV power, and hydropower are all 3%.

The Impact of Power Market on New Energy Accommodation

1) Increase of Peak Regulation Depth
This paper simulates the model with the condition that the minimum technical outputs of
some 600MW, 330MW and 300MW thermal power units are reduced to 50%, while the minimum technical outputs of some 135MW and 100MW thermal power units are reduced to 60%.

The capacity of new energy accommodation is increased by 5.84%. It can be seen that increasing the depth of peak regulation has obvious effect on improvement of new energy accommodation ability.

2) Spinning Reserve Optimization

It is assumed that the wind speed meets the standard normal distribution, and the confidence level is 80%. That is, 80% of the wind speed is greater than or equal to the required wind speed. The average wind power of the typical day is 1608.45MW and the standard deviation of wind power is 466.77 MW.

Spinning reserve optimization for the winter scene in the province is simulated. It can be obtained that the ability of new energy accommodation was improved by 1.11%, and spinning reserve optimization has some effect on the improvement of new energy accommodation ability.

3) Generation Rights Trade

The result of new energy generation rights trade is that parts of small thermal power plants with capacity of less than 50MW are suspended. The ability of new energy accommodation is increased by 7.76%. It can be seen that new energy generation rights trade is an effective means to promote new energy accommodation.

4) TOU Power Price

It is assumed that load variation of every hour is only affected by the elastic coefficient of three hours before and after. In order to ensure that the total load is roughly the same before and after the implementation of TOU electricity price, self-elasticity coefficient is assigned a value of -0.2, while mutual elastic coefficient is assigned a value of 0.033. The peak, flat, valley time price and time division are shown in Table II. The load curve with normal power price and TOU power price is shown in Figure 5.

<table>
<thead>
<tr>
<th>Time</th>
<th>Power Price/(yuan/kWh)</th>
<th>Time Division</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak</td>
<td>0.3</td>
<td>8: 00-12: 00, 18: 00-22: 00</td>
</tr>
<tr>
<td>Flat</td>
<td>0.2</td>
<td>12: 00-18: 00, 22: 00-24: 00</td>
</tr>
<tr>
<td>Valley</td>
<td>0.067</td>
<td>0: 00-8: 00</td>
</tr>
</tbody>
</table>

Figure 5. Load Curve with Normal Power Price and TOU Power Price.
It can be calculated through the simulation that the TOU power price can increase the capacity of new energy accommodation by 3.26%, thus promoting new energy accommodation.

5) Four Methods Above at The Same Time
This paper comprehensively uses four methods, including the increase of peak regulation depth, spinning reserve optimization, generation rights trade, TOU power price, and optimizes the winter scene of renewable integration. The capacity of new energy accommodation is 36,348.02 MWh, and it is increased by 9.98%. The ability of new energy accommodation before and after the optimization in power market is shown in Table III.

Table III. The Ability of New Energy Accommodation before and after Optimization.

<table>
<thead>
<tr>
<th>Optimization Way</th>
<th>New Energy Electricity Curtailment Rate (%)</th>
<th>New Energy Accommodation Electricity (MWh)</th>
<th>Accommodation Ability Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Original Way</td>
<td>13.54</td>
<td>33,050.37</td>
<td>-</td>
</tr>
<tr>
<td>Increase of Peak Regulation Depth</td>
<td>8.49</td>
<td>34,981.70</td>
<td>5.84</td>
</tr>
<tr>
<td>Spinning Reserve Optimization</td>
<td>12.58</td>
<td>33,418.64</td>
<td>1.11</td>
</tr>
<tr>
<td>Generation Rights Trade</td>
<td>6.84</td>
<td>35,614.27</td>
<td>7.76</td>
</tr>
<tr>
<td>TOU Power Price</td>
<td>10.73</td>
<td>34,126.42</td>
<td>3.26</td>
</tr>
<tr>
<td>Four Optimization Methods at The Same Time</td>
<td>4.92</td>
<td>36,348.02</td>
<td>9.98</td>
</tr>
</tbody>
</table>

CONCLUSION

This paper studies on renewable integration optimization method, sets up the optimization scheduling model considering electricity curtailment rate in peak regulation as well as grid line transmission capacity constraint, and then further puts forward and analyzes the methods in power market that promote new energy accommodation.

This paper focuses on the effect of methods in power market, including the increase of peak regulation depth, spinning reserve optimization, generation rights trade, TOU power price, on new energy accommodation. The simulation results of the 2018 winter scene show that compared to original methods, new energy electricity curtailment rate can be reduced by 8.62% and new energy accommodation electricity can be increased by 9.98% through the optimization methods in this paper. In power market environment, the employment of the optimization methods can improve the new energy accommodation ability of power system and provide reference for the optimal dispatch of power system.

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