Optimal Scheduling Model of Virtual Power Plant and Thermal Power Units Participating in Peak Regulation Ancillary Service in Northeast China

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Abstract. In recent years, the rapid development of wind power generation and the low load growth rate have brought challenges to the peak regulation of power grid in Northeast China. In order to solve the peak regulation problem, virtual power plant (VPP) is proposed to participate in the peak regulation auxiliary service market in Northeast china, especially for deep peak regulation. Firstly, two modes of peak regulation in Northeast China are introduced in this paper, which are thermal power unit and VPP. With the definition of the peak regulation capacity for VPP, the Optimal Scheduling Model of VPP participating in peak regulation ancillary service is established. The simulations are carried out in MATLAB. The results show that the economy of peak regulation is significantly improved in peak regulation auxiliary service based on VPP.

1. Introduction

With the increase of wind power installed capacity and slow load development in Northeast China, a large number of thermal power units are shut down. Hence, the peak regulation becomes difficult [1]. When the load is low, the capacity of deep peak regulation is insufficient, which not only harms the stable operation of units, but also has high peak regulation cost [2]. So, a novel peak regulation ancillary service market is demanded In order to solve the peak regulation problem in Northeast China. Virtual power plant (VPP) is an efficient peak regulation technology integrating clean energy, energy storage and controllable load. Its peak regulation capacity is determined by controllable load and energy storage device [3].

In [4], a three-layer hierarchical scheduling scheme for deep peak regulation using energy-storage auxiliary thermal power generating unit was proposed. Its upper layer performs optimization with energy-storage and peak-regulation effects and economical optimal operation as objective. The middle layer optimizes the total output of thermal unit with minimum peak-regulation cost as objective. The lower layer optimizes the output of each unit with the goal of maximizing efficiency. In [5], a layered dispatching sequence and strategy of Pumped Storage-Thermal are proposed, and the hierarchical optimal dispatching model of combined thermal storage and peak regulation is established. The upper model optimizes the output of pumped storage units in order to maximize the dispatching benefits of pumped storage units; the lower model optimizes the output of thermal power units with the objective of minimizing the total peak regulation cost of the system. In [6], an optimal model for energy storage operators to participate in peak load regulation is established by bidding. In the day-ahead scheduling, operators participate in bidding, and predict the capacity of the energy storage system according to the second day peak load demand announced by the power trading center. The power trading center aims
at minimizing the peak regulation cost, and optimizes the scheduling plan, taking into account the prediction error of the energy storage system, with the maximum profit of itself. The charging and discharging output is optimized to make it profit from the market on the premise of meeting the bidding capacity.

The methods discussed above are only mentioned that thermal power units participate in the peak regulation market or energy storage cooperates with the thermal power units to participate in the peak regulation market. However, VPP technology is not applied to peak regulation market.

In this paper, VPP is proposed to participate in the peak regulation auxiliary service market in Northeast China. Firstly, two modes of peak regulation are introduced in this paper, which are thermal power unit and VPP. Based on the definition of reported price and capacity for VPP, the Optimal Scheduling Model of VPP participating in peak regulation ancillary service is established. The simulations are carried out in MATLAB. The results show that VPP technology can significantly improve the economy of peak regulation cost.

2. Peak regulation modes in Northeast China

2.1 Peak regulation by thermal power units
All the thermal power units participating in the power market are responsible for peak regulation. The peak regulation capacity of thermal power units depends on the ability to track load changes and unit parameters [7]. According to the different depth of peak regulation, peak regulation could be divided into deep peak regulation and basic peak regulation [8]. When the thermal power unit is in the state of deep peak regulation, oil is needed to support combustion. Therefore, the power generation cost of thermal power unit would increase greatly. Under different peak regulation depths, the unit generation cost under different depths of peak regulation is shown in Figure 1.

![Figure 1. Unit generation cost under different depths of peak regulation](image)

In Fig.1, when the peak regulation depth exceeds 55%, the unit power generation cost increases rapidly. In Northeast China, in order to encourage thermal power units to participate in deep peak regulation, economic compensation is given to units participating in deep peak regulation. Peak regulation auxiliary service is provided by the units participating in deep peak regulation. Therefore, when the peak regulation depth of units exceeds 55%, the generation revenue will be basically equal to that of rated state generation.

2.2 Peak regulation by VPP
In Northeast China, peak regulation by thermal power units is common method. To reduce the wind power abandonment rate, the capacity of thermal power units to participate in the power market is getting lower, and the deep peak regulation capacity of power system is becoming low. At present, peak regulation based on VPP has a great advantage, which not only solves the defect of deep peak regulation ability, but also reduces the wind power abandonment rate. The diagram of VPP participating in peak regulation auxiliary service market is shown in Figure 2.
In Fig.2, the capacity of VPP participating in peak regulation auxiliary service market is determined by the capacity of energy storage and controllable capacity of load. Controllable loads are listed with two common interruptible loads, which are electric water heater and electric vehicle. The VPP operators report the capacity and price. The final bid winning capacity of VPP is determined by the peak regulation auxiliary service market. Power users participating in peak regulation in the VPP should be compensated.

3. Definition of reporting capacity for participating ancillary markets

In the above two peak regulation modes, free peak regulation service is only provided by thermal power units. Thermal power units and VPP is applied to participate in the peak regulation auxiliary service market.

Generally, the peak regulation capacity is determined according to the price. In this paper, two peak regulation modes would be made a deep analysis in the reported price and capacity.

3.1 Reporting capacity and price of thermal power units

According to the trail regulatory measures in electric power peak regulation auxiliary market in Northeast China, thermal power units with peak regulation rate higher than 50% would be compensated in the auxiliary market. Then, the minimum peak regulation rate is 50%, and the defined maximum peak regulation rate is 70%. By the different degree of deep peak regulation, it could be divided into two stages, 50%-60% and 60%-70% [9]. The reported capacity of thermal power units participating in peak regulation auxiliary service market is determined [10].

The reported prices of deep peak regulation services in different stages are different, as shown in Table 1.

| Peak regulation rate of thermal power plant | Range of reported price (CNY/kWh) |
|--------------------------------------------|-----------------------------------|
| 50% - 60%                                  | 0-0.4                             |
| 60% - 70%                                  | 0.4-1                             |

In Table 1, with the increase of peak regulation rate, the price of unit peak regulation capacity is also increasing, because the thermal power units are prone to failure under the condition of deep peak load regulation.

3.2 Reporting capacity and price of VPP

By collecting the schedulable capacity of controllable load, the operator of VPP calculates and reports the adjustable capacity of the whole VPP participating in the auxiliary market. The peak regulation capacity of the VPP is determined by electric heat-storage boiler, electric water heater, electric vehicle and energy storage device. The above relationship can be expressed as (1):

\[ E_R = E_{HS} + E_{EWT} + E_{ES} + E_{EV} \] (1)
In (1), $E_R$ is the reported peak regulation capacity. $E_{HS}$ is the peak regulation capacity of heating-storage boiler. $E_{EWH}$ is the peak regulation capacity of electric water heater. $E_{ES}$ is the peak regulation capacity of energy storage device. $E_{EV}$ is the peak regulation capacity of electric vehicle.

In this paper, the price of VPP participating in peak regulation market is assumed in Tab.2.

### Table 2. Price assumption for Peak regulation compensation by VPP

| Time            | Range of reported price (CNY/kWh) |
|-----------------|-----------------------------------|
| Valley time     | 0-0.25                            |
| Flat load’s time| 0.25-0.6                          |
| Peak time       | 0.6-0.9                           |

4. Optimization model of thermal power units and VPP participating in peak regulation ancillary service market

#### 4.1 The Optimization objective function

The minimum dispatching cost is defined as the objective function, which is consisted by two parts:

1) Dispatching price of thermal power unit

$$C_1 = \sum_{i=1}^{T} \sum_{t=1}^{I} \sum_{k=1}^{K} [\gamma_{ik}^H a_t (E_{i,k}^H - E_{i,k}^U)]$$  

(2)

In (2), $T$ is the number of peak regulation periods. $I$ is the number of Thermal power unit. $K$ is the stage of deep peak regulation. $\gamma_{ik}^H$ is the price of the $i$th thermal power unit at time $t$. $a_t$ is the length of the interval. $E_{i,k}^H$ is the peak regulation capacity of the $i$th thermal power unit at time $t$. $E_{i,k}^U$ is the free peak regulation capacity of the $i$th thermal power unit.

2) Dispatching price of VPP

$$C_2 = \sum_{j=1}^{T} \sum_{t=1}^{J} \gamma_j^V E_{i,j}^V$$  

(3)

In (3), $J$ is the number of VPP. $\gamma_j^V$ is the electricity price of the $j$th VPP at time $t$. $E_{i,j}^V$ is the peak regulation capacity of the $j$th VPP at time $t$.

To sum up, the objective function can be expressed as:

$$\min(C_1 + C_2)$$  

(4)

#### 4.2 The constraint condition

The constraints include conventional constraints of thermal power units and related constraints of VPP.

1) Balance constraint of peak regulation capacity

$$E_t = E_t^H + E_t^V$$  

(5)

In (5), $E_t$ is the peak regulation power at time $t$, which is obtained from the demand curve of peak regulation. $E_t^H$ is the electricity that thermal power units participate in peak regulation at time $t$. $E_t^V$ is the electricity that VPP participate in peak regulation at time $t$.

2) Maximum and minimum peak regulation capacity constraint of thermal power units

$$E_t^{H_{\text{min}}} \leq E_t^H \leq E_t^{H_{\text{max}}}$$  

(6)

In (6), $E_t^{H_{\text{min}}}$ is the bid winning capacity of $i$th thermal power unit. $E_t^{H_{\text{max}}}$ are minimum and maximum peak regulation capacity of thermal power units.

3) Ramp rate constraint of thermal power unit

$$E_t^{R} \leq E_{t+1}^{R} - E_{t-1}^{R} \leq E_t^{R}$$  

(7)
In (7), \( E_{ij}^H \) is the Bid winning capacity of thermal power unit at time \( t \). \( E_{ij}^H \) and \( E_{ij}^D \) are the ramp coefficient.

4) Minimum up/ down time constraint

\[
\begin{cases}
(\lambda_{ij,t-1} - \lambda_{ij,t})(T_{on} - T_{off}) \geq 0 \\
(\lambda_{ij,t} - \lambda_{ij,t-1})(T_{on} - T_{off}) \geq 0
\end{cases}
\]  \( \text{(8)} \)

In (8), \( \lambda_{ij} \) is the up/down state variable of the \( i \)th thermal power unit at time \( t \). \( \lambda_{ij,t-1} \) is the up/down state variable the last moment. \( T_{on} \) is the minimum continuous startup time. \( T_{on}^m \) is the continuous operate time of the \( i \)th thermal power unit at time \( t \). \( T_{off} \) is the minimum continuous shutdown time. \( T_{off}^m \) is the continuous shutdown time of the \( i \)th thermal power unit at time \( t \).

5) Maximum and minimum peak regulation capacity constraint of VPP

\( E_{j}^{v \text{min}} \leq E_{j}^v \leq E_{j}^{v \text{max}} \)  \( \text{(9)} \)

In (9), \( E_{j}^v \) is the bid winning capacity of \( j \)th VPP. \( E_{j}^{v \text{min}} \) and \( E_{j}^{v \text{max}} \) are minimum and maximum peak regulation capacity of VPP.

6) Ramp rate constraint of VPP

\( E_{D}^v \leq E_{j,t}^v - E_{j,t-1}^v \leq E_{U}^v \)  \( \text{(10)} \)

In (10), \( E_{j,t}^v \) is the Bid winning capacity of VPP at time \( t \). \( E_{U}^v \) and \( E_{D}^v \) are the ramp coefficient.

5. Simulation and analysis

In order to verify the correctness of the model established in this paper, a typical case of deep peak regulation demand is constructed. In a certain area, peak regulation is required from 12:15 to 13:30, as shown in Table 3.

| Time       | Peak regulation demand(MW) |
|------------|-----------------------------|
| 12:15-12:30| 600                         |
| 12:30-12:45| 560                         |
| 12:45-13:00| 520                         |
| 13:00-13:15| 480                         |
| 13:15-13:30| 450                         |

Table 3. Peak regulation demand in a certain area

Three thermal power units and two virtual power plants are considered to solve the peak regulation problem. The thermal power units and virtual power plants jointly participate in the peak regulation auxiliary service market. The parameters of the unit are shown in Table 4.

| Parameters | Rated capacity (MW) | Minimum up/ down time (h) | Ramp rate (MW/min) |
|------------|---------------------|---------------------------|-------------------|
| H1         | 400                 | 8                         | 0.4               |
| H2         | 300                 | 6                         | 0.4               |

Table 4. The parameters of units
The reported prices and capacities of different units participating in peak regulation auxiliary service market are different, as shown in Table 5.

### Table 5. The reported prices and capacities of units

| Parameters | Free peak regulation capacity (MW) | Paid peak regulation capacity (MW) | Reported Price (CNY/kWh) |
|------------|-----------------------------------|-----------------------------------|--------------------------|
|            | I                                 | II                                | I                        | II                        |
| H1         | 200                               | 40                                | 40                       | 0.36                      | 0.72                      |
| H2         | 150                               | 30                                | 30                       | 0.34                      | 0.68                      |
| H3         | 100                               | 20                                | 20                       | 0.32                      | 0.64                      |
| VPP1       | 0                                 | 25                                |                           | 0.52                      |
| VPP2       | 0                                 | 15                                |                           | 0.50                      |

In Table 5, Thermal power units include free peak regulation capacity and paid peak regulation capacity. The paid peak regulation capacity is divided into two parts according to different peak regulation rates, and the price is also different. The peak regulation capacity provided by VPP is paid, because compensation needs to be provided to dispatch controlled load.

In view of whether VPP participates in the peak regulation auxiliary market, the economic efficiency of peak regulation is analysed respectively.

1. Thermal power units participates in the peak regulation auxiliary market

   Peak regulation task is undertaken by three thermal power units, and the peak load regulation capacity of the units is shown in Figure 3.

   ![Figure 3. Peak regulation capacity of units](image)

   In Fig.3, demand for peak regulation is decreasing. Therefore, the peak regulation capacity of each unit is decreasing. From 13:00 to 13:30, peak regulation task can be completed only by the free peak regulation capacity provided by thermal power units.

2. VPP participates in the peak regulation auxiliary market
In order to study the economy of virtual power plants participating in peak regulation auxiliary service market, two virtual power plants participate in the operation of the market. The peak regulation capacity of each unit is shown in Figure 4.

![Figure 4. Peak regulation capacity of units](Image)

In Fig.4, compared with the above, peak regulation task is undertaken by five units. After 12:45, due to the high reported price of VPP participating in the peak regulation auxiliary service market, the peak regulation capacity of thermal power units is used by power grid.

According to Table 4, the peak regulation cost can be calculated. The peak regulation costs of the two conditions are shown in Table 6.

| Conditions                                      | Peak regulation cost(CNY) |
|------------------------------------------------|---------------------------|
| Thermal power units participates in the peak regulation auxiliary market | 37200                     |
| VPP participates in the peak regulation auxiliary market          | 34750                     |

In Table 6, compared with thermal power units participating in peak regulation, the cost of VPP participates in the peak regulation reduces by 2450. The simulation results show that the economy of peak regulation auxiliary service market is improved after the VPP is participated.

6. Conclusion
In this paper, two peak regulation methods are introduced in Northeast China, and the advantages of VPP to solve the deep peak regulation problem are studied. The reported capacity and price of thermal power units and VPP participating in peak regulation auxiliary service market are defined. The dispatching model of VPP and thermal power units participating in peak regulation auxiliary service market is established. Finally, the model with the lowest scheduling cost is established in MATLAB. The simulation results show that the economy of peak regulation is significantly improved based on VPP participating in peak regulation auxiliary service market. Therefore, in Northeast China, it is very meaningful to fully excavate the peak regulation capacity of VPP.

7. References
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