Optimal Scheduling Model of Peak-shaving Resources Based on the Quotation for Peak-shaving Capacity

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Abstract—The development of the ancillary service market for peak shaving has led to new options for flexible modification of conventional thermal power units and raised the level of utilization of new energy resources. However, the peak shaving schedule is worked out without consideration of the unit power generation schedule and the reserve schedule. This paper proposes a day-ahead optimization model for scheduling the peak shaving resources based on the quotation for the peak shaving capacity of the thermal power unit, which could be used to optimize the unit's peak shaving schedule, power generation schedule, and reserve schedule as a whole. Based on the established peak shaving compensation benchmark, pricing type, and pricing mechanism of the thermal power units, this model could take the impact on the unit's power generation schedule resulting from the power generation cost and peak shaving compensation cost into account. Through the analysis of cases selected from typical provinces in China, the results show that the model in this paper could effectively connect the peak shaving ancillary service market and the energy market, and minimize the costs of the peak shaving ancillary services and energy.

Keywords- Ancillary service market; peak shaving resources; peak shaving schedule; power generation schedule; mixed integer programming model

1. INTRODUCTION

In recent years, important reform measures have been taken in the national plan for energy resources to promote the development of clean energy resources such as hydropower, wind power, and solar power [1-3]. Currently, the power generation scheduling and management model adopted in China has relatively rigid characteristics with little flexibility. The existing power generation scheduling and management model are not conducive to promote the consumption of clean energy [4].

The peak shaving ancillary service market has been built for the main purpose of developing the peak shaving potential of existing market participants. This measure has introduced a market mechanism that could address the problem of peak shaving and consumption of new energy during valley times. In foreign power market, the scheduling of the peak shaving resources mainly depends on the short-term wholesale power market. Present research includes the impact of large-scale new energy resources on the power market, and the design of power market [5-6]. For example, in literature [6], the impacts of large-scale new energy resources on the energy market and capacity market. have been studied.

ICEMME 2022, November 18-20, Nanjing, People's Republic of China

DOI 10.4108/eai.18-11-2022.2326912

China has carried out a series of studies on designing the market mechanism for peak shaving ancillary services [7-9]. In literature [7], in light of situations where it is difficult for peak shaving units to get reasonable compensation and it is not conducive to encourage the units to join in the system peak shaving applications under the energy-saving scheduling operations, it proposes a novel unit peak shaving compensation mechanism. In literature [8], a pricing method and compensation mechanism for compensating wind power ancillary services was proposed. In literature [9], a peak-valley benchmark tariff model with two-part pricing mechanism at the two power generation sides has been established. In this model, the two-part tariff mechanism is used as a substitute for the existing one-part tariff mechanism, to solve the problem where it is impossible to stimulate peak shaving operations in the one-part tariff mechanism due to the apportioned fixed cost.

In foreign power market, auxiliary services mainly include frequency modulation, voltage regulation, reserve capacity, black start and so on. Peak shaving doesn't fall into the range of ancillary services. It is instead achieved through the spot market. In the spot market, price signals are used to guide the units to change the power output level, thus realizing the aim of peak shaving. Considering that the peak shaving market and the energy market are currently two independent markets in China, this method cannot be directly applied to the scheduling operation of China's power system.

In view of the above problems, with the lowest power generation cost and peak shaving compensation cost as the optimization goal, a day-ahead optimization method to schedule the peak shaving resources based on the quotation for the peak shaving capacity of the thermal power unit has been established in this paper. Based on the established peak shaving compensation benchmark, pricing type, and pricing mechanism of the thermal power units, overall consideration has been given to the impact on the unit power generation schedule resulting from the power generation cost and the peak shaving compensation cost. Besides considering the system load balance constraint, spinning reserve constraint, as well as the generalized power constraint, reserve capacity constraint, and ramp rate constraint of the thermal power units, and other conventional economic scheduling constraints, a coupling constraint has been established that particularly covers the power generation schedule, peak shaving schedule, and reserve schedule for the thermal power unit. By introducing the linearization method, this optimization model can be converted into a mixed integer linear programming model.

2. OPTIMIZATION MODEL

2.1 Objective function

In the optimization model, the day-ahead power generation schedule and the day-ahead peak shaving schedule for the thermal power unit need to be optimized as a whole.

According to the rules of the trading organization regarding the peak shaving ancillary services, a day-ahead peak shaving price curve is provided for the thermal power unit furnishing the peak shaving ancillary services. When the scheduling department prepares the day-ahead power generation schedule for this unit, the power generation cost is also taken into consideration. Therefore, this optimization model for scheduling the peak shaving resources based on the quotation for the peak shaving capacity is established for the purpose of lowering down the total system peak shaving cost and power generation cost to the minimum level. The specific objective function is as shown below:

$$\min J = \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{j=1}^{J}\left[\left(a_{j,n}\left(p_j^{t,n}\right)^2 + b_{j,n}p_j^{t,n} + c_{j,n}u_j^{t,n}\right) + \sum_{m=1}^{M}\lambda_{j,n}^{m}E_{j,n}^{m,t+} + \sum_{m=1}^{M}\lambda_{j,n}^{m}E_{j,n}^{m,t-}\right] \tag{1}$$

where T refers to the number of scheduling periods in a day. N refers to the number of regions. J refers to the number of thermal power units. M refers to the number of the stages of the price during peak shaving periods for the thermal power units. $a_{j,n}$ refers to the coal consumption coefficient of the quadratic term for the thermal power unit j as indicated in region n. $b_{j,n}$ refers to the coal consumption coefficient of the first-order term for the thermal power unit j in region n. $c_{j,n}$ refers to the coal consumption coefficient of the constant term for the thermal power unit j in region n. $p_j^{t,n}$ refers to the power generated by the thermal power unit j in time period t in region n. $u_j^{t,n}$ refers to the on/off status of the thermal power unit j in time period t in region n, and it is a discrete variable ranging from 0 to 1. Especially, $u_j^{t,n}=1$ means the unit is on during this time period. Otherwise, it means the unit is off during this time period. $\lambda_{j,n}^{m}$ refers to the price level at the m peak shaving pricing stage for the thermal power unit j in region n. $E_{j,n}^{m,t+}$ refers to the paid electricity amount for peak shaving applications at the m peak shaving pricing stage when the thermal power unit j in region n is in the time period t providing positive reserve. $E_{j,n}^{m,t-}$ refers to the paid electricity amount for peak shaving applications at the m peak shaving pricing stage when the thermal power unit j in region n is in the time period t providing negative reserve.

In Formula (1), the first part $\left(a_j\left(p_j^{t,n}\right)^2 + b_j p_j^{t,n} + c_j u_j^{t,n}\right)$ is the power generation cost of the thermal power unit j in region n in time period t, and it is the quadratic function of the power generated from the unit. The second part $\sum_{m=1}^{M}\lambda_{j,n}^{m}E_{j,n}^{m,t+}$ is the paid cost for the peak shaving services required for the thermal power unit j in region n in the time period t after the positive reserve is provided. The third part $\sum_{m=1}^{M}\lambda_{j,n}^{m}E_{j,n}^{m,t-}$ is the paid cost for the peak shaving services required for the thermal power unit j in region n in the time period t after the negative reserve is provided.

2.2 Constraints

The constraint conditions include regional load demand balance constraint, spinning reserve constraint, the generation power boundary constraint for thermal power units, the minimum on/off time constraint for thermal power units, the ramp rate constraint for thermal power units, new energy generation power constraint, transmission line capacity constraint, etc. For more information, it could be found in [10-12]. The paid peak shaving capacity coupling constraint of a thermal power unit is as follows.

$$E_{j,n}^{m,t-} \geq \overline{w}_{j,n}^{m} P_j^{\max,n} - (p_j^{t,n} - R_{j,n}^{t,-}) - \Delta E_{j,n}^{m,t-} \tag{2}$$

$$E_{j,n}^{m,t-} \leq \overline{w}_{j,n}^{m} P_j^{\max,n} - \underline{w}_{j,n}^{m} P_j^{\max,n} \tag{3}$$

$$\Delta E_{j,n}^{m,t-} \leq x_{j,n}^{m,t-} \left[\underline{w}_{j,n}^{m} P_j^{\max,n} - (p_j^{t,n} - R_{j,n}^{t,-}) \right] \tag{4}$$

$$\Delta E_{j,n}^{m,t-} \geq 0 \tag{5}$$

$$E_{j,n}^{m,t-} \geq 0 \tag{6}$$

$$E_{j,n}^{m,t+} \geq \overline{w}_{j,n}^{m} P_j^{\max,n} - (p_j^{t,n} + R_{j,n}^{t,+}) - \Delta E_{j,n}^{m,t+} \tag{7}$$

$$E_{j,n}^{m,t+} \leq \overline{w}_{j,n}^{m} P_j^{\max,n} - \underline{w}_{j,n}^{m} P_j^{\max,n} \tag{8}$$

$$\Delta E_{j,n}^{m,t+} \leq x_{j,n}^{m,t+} \left[\underline{w}_{j,n}^{m} P_j^{\max,n} - (p_j^{t,n} + R_{j,n}^{t,+}) \right] \tag{9}$$

$$\Delta E_{j,n}^{m,t+} \geq 0 \tag{10}$$

$$E_{j,n}^{m,t+} \geq 0 \tag{11}$$

where $\overline{w}_{j,n}^{m}$ refers to the upper boundary of the load rate in the m peak shaving pricing stage for the thermal power unit j in region n. $\underline{w}_{j,n}^{m}$ refers to the lower boundary of the load rate in the m peak shaving pricing stage for the thermal power unit j in region n. $\Delta E_{j,n}^{m,t-}$ and $\Delta E_{j,n}^{m,t+}$ are auxiliary variables. $x_{j,n}^{m,t-}$ and $x_{j,n}^{m,t+}$ are discrete variables ranging from 0~1, also called the auxiliary variables. This constraint restricts the paid peak shaving capacity at each price stage for the thermal power unit j.

3. Linearization method

In the paid peak shaving capacity coupling constraint for the thermal power unit, there are nonlinear terms multiplied by discrete variables and continuous variables, which are $x_{j,n}^{m,t-} p_j^{t,n}$, $x_{j,n}^{m,t-} R_{j,n}^{t,-}$, $x_{j,n}^{m,t+} p_j^{t,n}$, and $x_{j,n}^{m,t+} R_{j,n}^{t,+}$. The four nonlinear terms are linearized separately as below.

1) Linearization of $x_{j,n}^{m,t-} p_j^{t,n}$:

Introduce auxiliary variable $v_{j,n}^{m,t,1}$ and $v_{j,n}^{m,t,2}$, where $v_{j,n}^{m,t,1}{=}x_{j,n}^{m,t-}p_j^{t,n}$, so the nonlinear term $x_{j,n}^{m,t-}p_j^{t,n}$ can be expressed with the following linear constraints:

$$v_{j,n}^{m,t,1}+v_{j,n}^{m,t,2}=p_j^{t,n} \tag{12}$$

$$0\le v_{j,n}^{m,t,1}\le x_{j,n}^{m,t-}P_j^{\max,n} \tag{13}$$

$$0\le v_{j,n}^{m,t,2}\le (1-x_{j,n}^{m,t-})P_j^{\max,n} \tag{14}$$

2) Linearization for $x_{j,n}^{m,t-}R_{j,n}^{t,-}$:

Introduce auxiliary variable $y_{j,n}^{m,t,1}$ and $y_{j,n}^{m,t,2}$, where $y_{j,n}^{m,t,1}{=}x_{j,n}^{m,t-}R_{j,n}^{t,-}$, so the nonlinear term $x_{j,n}^{m,t-}R_{j,n}^{t,-}$ can be expressed with the following linear constraints:

$$y_{j,n}^{m,t,1}+y_{j,n}^{m,t,2}=R_{j,n}^{t,-} \tag{15}$$

$$0\le y_{j,n}^{m,t,1}\le x_{j,n}^{m,t-}\Delta P_{j,down}^{n}\Delta T \tag{16}$$

$$0\le y_{j,n}^{m,t,2}\le (1-x_{j,n}^{m,t-})\Delta P_{j,down}^{n}\Delta T \tag{17}$$

3) Linearization for $x_{j,n}^{m,t+}p_j^{t,n}$:

Introduce auxiliary variable $k_{j,n}^{m,t,1}$ and $k_{j,n}^{m,t,2}$, where $k_{j,n}^{m,t,1}{=}x_{j,n}^{m,t+}p_j^{t,n}$, so the nonlinear term $x_{j,n}^{m,t+}p_j^{t,n}$ can be expressed with the following linear constraints:

$$k_{j,n}^{m,t,1}+k_{j,n}^{m,t,2}=p_j^{t,n} \tag{18}$$

$$0\le k_{j,n}^{m,t,1}\le x_{j,n}^{m,t+}P_j^{\max,n} \tag{19}$$

$$0\le k_{j,n}^{m,t,2}\le (1-x_{j,n}^{m,t+})P_j^{\max,n} \tag{20}$$

4) Linearization for $x_{j,n}^{m,t+}R_{j,n}^{t,+}$:

Introduce auxiliary variable $h_{j,n}^{m,t,1}$ and $h_{j,n}^{m,t,2}$, where $h_{j,n}^{m,t,1}{=}x_{j,n}^{m,t+}R_{j,n}^{t,+}$, so the nonlinear term can be expressed with the following linear constraints:

$$h_{j,n}^{m,t,1}+h_{j,n}^{m,t,2}=R_{j,n}^{t,+} \tag{21}$$

$$0\le h_{j,n}^{m,t,1}\le x_{j,n}^{m,t+}\Delta P_{j,up}^{n}\Delta T \tag{22}$$

$$0\le h_{j,n}^{m,t,2}\le (1-x_{j,n}^{m,t+})\Delta P_{j,up}^{n}\Delta T \tag{23}$$

Combining formulas (12)~(23), formulas (4) and (9) in the paid peak shaving capacity constraint for the thermal power unit can be modified as below, respectively.

$$\Delta E_{j,n}^{m,t-}\le x_{j,n}^{m-}\underline{w}_{j,n}^{m}P_j^{\max,n}-v_{j,n}^{m,t,1}+y_{j,n}^{m,t,1} \tag{24}$$

$$\Delta E_{j,n}^{m,t+}\le x_{j,n}^{m+}\underline{w}_{j,n}^{m}P_j^{\max,n}-k_{j,n}^{m,t,1}-h_{j,n}^{m,t,1} \tag{25}$$

The paid peak shaving capacity coupling constraints for a thermal power unit after linearization include formulas (2)~(3), formulas (5)~(8), formulas (10)~(11), and formulas (12)~(25).

4. TESTING OF CASES

4.1 Introduction of the case system

By taking a typical provincial power grid in China as an example, we analyse the impact on the total system power generation cost of the joint clearing method by integrating the energy market and the peak shaving market in the day-ahead market. In this system, the total installed capacity is 20.86 GW for thermal power units, 9.9 GW for hydroelectric turbines, 13.17 GW for wind turbines, and 8.64 GW for solar units.

In the provincial case, the peak shaving pricing model and the pricing mechanism for the thermal power unit are given in Table 1.

TABLE 1. PEAK SHAVING PRICING MODEL AND PRICING MECHANISM FOR THE THERMAL POWER UNIT.

Price Stage	Unit Load Rate	Upper Boundary of Peak Shaving Price (￥/kWh)	Lower Boundary of Peak Shaving Price (￥/kWh)
1st Stage	40% ≤ Load rate < 50%	0.4	0
2nd Stage	Load rate < 40%	1.0	0.4

In this case, we believe that the quotation listed in each stage for the thermal power unit is the upper boundary of the price. That is, the peak shaving prices in the first stage are 0.4 yuan per kilowatt hours, and the peak shaving prices in the second stage are 1.0 yuan per kilowatt hours.

4.2 Analysis of test results

Research has been conducted for the optimization of the model for scheduling the peak shaving resources based on the quotation for the peak shaving capacity, and comparative analysis has been done on the impact on the system cost when co-clearing is applied, by integrating the power generation schedule and the peak shaving schedule.

Firstly, the power generation schedule and the peak shaving schedule of a thermal power unit are separately cleared. The power generation cost for the thermal power unit and the peak shaving compensation cost for considering the reserve schedule are shown in Table 2.

TABLE 2. POWER GENERATION COST AND PEAK SHAVING COST OF THE UNIT AT SEPARATE CLEARING.

Power Generation Cost (10^4￥)	Total Peak Shaving Compensation Cost (10^4 ￥)
4,178.5	6,555.3

For comparison, the power generation schedule and the peak shaving schedule of the thermal power unit are jointly cleared. The power generation cost for the thermal power unit and the peak shaving compensation cost for considering the reserve schedule are shown in Table 3.

TABLE 3. POWER GENERATION COST AND PEAK SHAVING COST OF THE UNIT AT JOINT CLEARING (CO-CLEARING).

Power Generation Cost (10^4￥)	Total Peak Shaving Compensation Cost (10^4 ￥)
4,581.2	0

As shown in Table 2 and Table 3, when the power generation schedule and the peak shaving schedule of the unit are separately cleared, due to failure to consider the impact of the unit reserve schedule on the peak shaving cost, the power generation cost obtained at this time is significantly lower than that obtained at joint clearing for the unit, but the total cost of the system after the unit has provided the reserve at separate clearing, is significantly larger than that at joint clearing.

In the joint clearing mode, since the coupling relations between the power generation schedule and the peak shaving schedule of the unit are taken into account, the peak shaving ancillary service provided by other units can be avoided by adjusting the power generation schedules for some units when the total minimum cost of the system is set as the objective for optimization, thus reducing the peak shaving ancillary service cost of the system.

5. CONCLUSION

In reality, the power generation schedule and peak shaving schedule for the thermal power unit are formulated without comprehensive consideration, and this condition is not conducive to obtaining overall benefits for society. To resolve this issue, we propose a day-ahead optimization method to schedule the peak shaving resources based on the quotation for the peak shaving capacity of the thermal power unit in this paper. Based on the established peak shaving compensation benchmark, pricing type, and pricing mechanism of the thermal power units, overall consideration has been given to determining the day-ahead power generation schedule, reserve schedule, and peak shaving schedule for a thermal power unit, to realize the formulation of the peak shaving schedule and the power generation schedule of the unit on an integrated and coordinated basis. This can effectively connect the peak shaving ancillary service market with the energy market, minimize the system cost to be paid for the peak shaving ancillary service and energy, improve the overall benefits to society, and enhance performance to promote the consumption of new energy.

Acknowledgments. This work is supported by State Grid Corporation Science and Technology Project (4000-202057046A-0-0-00).

REFERENCES

[1] Gao Zhiyuan, Xu Liang, Zhao Lei, Cao Yang, Xue Kunyuan, and Zhang Jun. Research on Consumption Framework Based on Clean Energy Value Analysis. Distribution & Utilization, 2021, 38(2): 65-69.

[2] Ma Li, Huang Liming, Xue Song, et al. Key Issues for orderly Operation of China's New Electricity Market Reform Pilot. Power, 2017, 50(4): 17-22.

[3] Gao Dan, Kong Geng, Ma Linwei, Yan Xiaohui, and Zhang Heng. Energy Development Status

and Developing Focus of Varied Regions in China. Strategic Study of CAE, 2021, 23(1): 1-8.
[4] Xie Bing, Yang Xiaowei, Yu Zhuangzhuang, Luo Gang, and Guo Ruipeng. Two-stage optimization model for annual rolling generation scheduling considering open and impartial dispatching. Power Automation Equipment, 2018, 38(12): 155-161.
[5] Meibom P., Barth R., Hasche B., et al. Stochastic optimization model to study the operational impacts of high wind penetrations in Ireland. IEEE Transactions on Power Systems, 2011, 26(3): 1367-1379.
[6] E. Ela, M. Milligan, A. Bloom, A. Botterud, A. Townsend, and T. Levin. Evolution of Wholesale Electricity Market Design with Increasing Levels of Renewable Generation. NREL/TP-5D00-61765 September 2014.
[7] Li Yanqing, Li Haoshan. Improvement of compensation mechanism on peak-regulating auxiliary service for thermal power unit with energy saving dispatch. Heilongjiang Power, 2014, 36(3): 194-206.
[8] Sun Huali, Wang Bangcan, and Luo Linglin. Research on Pricing for Wind Power Ancillary Services Compensation. Heilongjiang Power, 2015, 43 (5): 61-64.
[9] Wang Yuwei. The Research of Two-part and Time-of-use Benchmark Power Price at Generation Side Oriented to Peak Load Regulation. Dalian University of Technology, 2013.
[10] Dong Cun, Li Mingjie, Fan Gaofeng, Huang Yuehui, and Li Xiaofei. Research and Application of Renewable Energy Accommodation Capability Evaluation Based on Time Series Production Simulation. Electric Power, 2015, 48(12): 166-172.
[11] Cao Yang, Li Peng, Yuan Yue, Zhang Xinsong, Guo Siqi, and Zhang Chengfei. Analysis on Accommodating Capability of Renewable Energy and Assessment on Low-carbon Benefits Based on Time Sequence Simulation. Automation of Electric Power Systems, 2014, 38(17): 60-66.
[12] Liu Chun, Qu Jixian, and Shi Wenhui. Evaluating Method of Ability of Accommodating Renewable Energy Based on Probabilistic Production Simulation. Proceedings of the CSEE, 2020, 40(10): 3134-3144.