E3S Web of Conferences **218**, 02027 (2020) https://doi.org/10.1051/e3sconf/202021802027
ISEESE 2020

Dynamic paid peak shaving benchmarks and bidding strategies adapted to the high proportion of new energy system

Huanhuan Luo[1], Yang Zhao[2,a], Tianhang Wang[2], Yifan Wang[2], Hao Wang[2], Weichun Ge[1], Chuang Liu[2] and Yibo Wang[2]

[1]School of Electrical Engineering Shenyang University of Technology Shenyang 110006 CN
[2]School of Electrical Engineering Northeast Electric Power University Jilin 132012 CN

Abstract. This article mainly analyze the shortcomings of the inherent peak shaving auxiliary service mechanism in the high-proportion of new energy access scenarios in Northeast China, which restricts the enthusiasm of thermal power units to participate in peak shaving. For this reason, a dynamic peak shaving compensation benchmark is proposed which follows load changes. At the same time, in order to standardize market behavior and facilitate market supervision, a guiding formula is proposed for quotation of thermal power units. Based on the above, a dynamic auxiliary service market mechanism is established which used actual operating data of Liaoning province power grid as a calculation example to verify that the mechanism can effectively improve the enthusiasm of thermal power units to participate in peak shaving, which is conducive to market operation and supervision as well.

1 Introduction

The Northeast Energy Regulatory Bureau issued the "Operation Rules for the Northeast Electric Power Auxiliary Service Market" in November 2016. So far, the mechanism has achieved good results in new energy consumption. However, as the proportion of new energy in the current energy system in Northeast China has increased, the Northeast region is facing increasingly prominent peak shaving problems. The problems limit the further development of new energy power generation and even leads to reduction in the use of new energy sources. Literature [1] studies the existing methods and efficiency analysis of new energy consumption. Literature [2] aims at maximizing the expected revenue of wind power plants and proposes a day-ahead market dispatch model that considers source load and peak shaving. Literature [3] studies the self-dispatch problems of price takers with wind power and thermal power production capacity with the aid of cyber-physical systems that support the power market manager decision-making. Literature [4-7] considers the impact of wind power consumption on the system. In response to the predicament of Northeast Power Grid peak shaving, this paper has proposed a dynamic paid peak-shaving benchmark based on load fluctuations, established a bidding mechanism which is conducive to market supervision, and finally established a multi-objective bidding dispatch model and peak shaving auxiliary service (hereinafter referred to as PSAS) market. At the same time, we use the actual data of the Liaoning Province power grid as an example to perform calculation and analysis to verify the superiority of the new dynamic PSAS market bidding mechanism (hereinafter referred to as the dynamic mechanism).

2 Design of dynamic mechanism

2.1 Existing mechanism and its problems

In the current mechanism, the Northeast Energy Regulatory Bureau divides peak PSAS into two types: free PSAS and paid PSAS. The free PSAS refers to the service provided by the power-on thermal power unit (Hereinafter referred to as TPU) by reducing its output value above the paid peak-shaving reference, while the paid PSAS refers to the power-on TPU reducing its output to below the paid peak-shaving reference. The paid peak shaving benchmarks for TPUs under the current mechanism is the average load rates of TPU. During the non-heat-providing period, pure-condensing TPU's benchmark is 50%.

Current peak-shaving compensation mechanism: in the day-ahead markets, the TPU reported the adjustable range of output and tiered quotation. In the intra-day markets, the dispatching center called the PSAS according to the actual peak-shaving demand and the quotation from low to high. At the end of the day, the trading center counts the paid peak shaving power of TPUs and clears the PSAS fees.

Under the current mechanism, the paid peak shaving benchmark for any TPU is a fixed value in a certain period. For example, in the non-heating period, the paid peak shaving benchmark for a 400MW pure coal-fired power unit is 200MW, which means 50% of its rated capacity.

Figure 1 shows the above unit's planned output value curve, after-participating-in-PSAS output value (PSAS output value) curve and the reference curve of the paid peak shaving benchmark under the current mechanism.

* Corresponding author: zhaoyangneepu@163.com

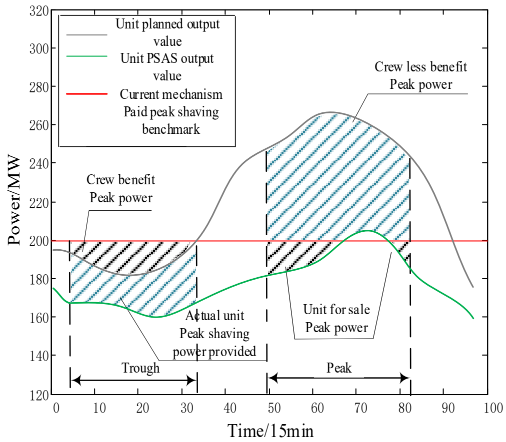

Fig1. Diagram of peak-shaving output value of TPU under current mechanism

From Figure 1, we can see that the paid peak shaving benchmark for the TPU in a specific period is a fixed value (red line). During the trough period, the planned output of the TPU is less than the paid peak shaving benchmark. After participating in PSAS, the actual electricity reduced (Trough period, blue area in Figure.1) will be less than the electricity reduced based on the paid peak shaving benchmark, So the TPU in the low load period obtain more peak shaving compensation. In the same way, during the peak load period, because the planned output value of the TPU is much higher than the paid peak shaving benchmark, the TPU provides a large amount of down-peaking electricity for free, resulting in a substantial reduction in the peak shaving revenue of the TPU. The cost of free PSAS electricity during the peak period is much larger than the more profitable PSAS electricity income during the trough period (the blue area in the peak period is much larger than the black area in the trough period), which has greatly reduced the enthusiasm of the TPU to participate in peak shaving. Under the current mechanism, if the TPU wants to recover the cost of free PSAS electricity in peak periods, there have been violations such as driving up market peak shaving prices, resulting in high peak shaving quotations for each TPU. The high quotation ultimately leads to a high market-clearing price.

In summary, there are two problems with the current market mechanism: First, the peak shaving benchmark is fixed, resulting in low enthusiasm for peak shaving of the TPU. Second, the TPU jointly drive up the PSAS price, which makes the PSAS price higher. This article mainly focuses on the two issues above to design a new PSAS market bidding mechanism.

2.2 Dynamic PSAS market bidding mechanism

To solve the two problems in the current mechanism mentioned above, this article decides to formulate a floating peak shaving benchmark based on load fluctuations and establish a quotation rule that is conducive to market supervision. These two are collectively called as the dynamic PSAS market bidding mechanism.

2.2.1 Establishment of floating peak shaving benchmark

This article suggests that the net load forecast value should be allocated to each TPU according to the proportion of its' installed capacity. We regard it as the planned output value under the dynamic mechanism, and the planned output value of each unit now is called the dynamic peak shaving benchmark. Therefore, the dynamic peak shaving benchmark and the fluctuation trend of the load are also roughly the same.

2.2.2 Cost analysis of unit peak shaving

When the TPU participates in the up-peak shaving service, its' electricity fees income is increased. Therefore, the new energy power plants do not need to pay the TPU for the up PSAS fees. Therefore, only the cost of the TPU participating in the down PSAS is considered.

The cost of the unit's participation in down PSAS is mainly divided into two parts. One part is the loss of power generation revenue due to the power reduction, which is referred as the opportunity cost, and the other part is the coal consumption cost caused by the change in the combustion efficiency of the unit due to the power reduction.

The total cost of the TPU participating in down PSAS can be expressed as:

$$\alpha_{i,t} = \alpha_{\mathrm{opp},i,t} + \alpha_{\mathrm{coal},i,t} = \beta_{\mathrm{elc,t}} \left(P_{\mathrm{plan},i,t} - P_{i,t} \right) + \beta_{\mathrm{coal,t}} \left(F_i(P_{i,t}) - F_i(P_{\mathrm{plan},i,t}) \right) \tag{1}$$

$$F_i(P_{i,t,\mathrm{plan}}) = a_i P_{i,t,\mathrm{plan}}^2 + b_i P_{i,t,\mathrm{plan}} + c_i \tag{2}$$

Where $\alpha_{i,t}$ represents the total cost of down peak shaving, $\alpha_{opp,i,t}$ indicates the opportunity cost, $\alpha_{coal,i,t}$ indicates the coal consumption cost, $\beta_{elc,t}$ indicates the real-time electricity price, $\beta_{coal,t}$ indicates the real-time coal price, $P_{plan,i,t}$ is the planned output value of the TPU, $P_{i,t}$ is the actual output value of the TPU, $F_i(P_{i,t})$ function is the characteristic curve of coal consumption. i is the unit number.

And we use variable $\Delta P_{i,t}$ to replace $P_{i,t}$

That is:

$$\Delta P_{i,t} = P_{i,t,\mathrm{plan}} - P_{i,t} \tag{3}$$

From this, we can deduce that the marginal cost of the lower regulation is

$$\theta_{\mathrm{c},i,t} = \frac{\partial \alpha_{i,t}}{\partial \Delta P_{i,t}} = 2a_i \beta_{\mathrm{coal.t}} \Delta P_{i,t} - 2a_i \beta_{\mathrm{coal.t}} P_{i,t,\mathrm{plan}} - b_i \beta_{\mathrm{coal.t}} + \beta_{\mathrm{elc.t}} \tag{4}$$

$\theta_{c,i,t}$ is the marginal cost of unit i to provide PSAS at time period t.

2.2.3 Formulation of quotation rules

To formulate a more reasonable quotation rule, we should first consider the problem from the perspective of the TPU, to allow all TPUs to implement their quotation strategy as far as possible. The goal of each TPU is to maximize its revenue, that is

$$\max \zeta_{i,t} = \psi_{i,t} - \alpha_{i,t} \tag{5}$$

$\zeta_{i,t}$ is the profit earned by unit i at time t by providing PSAS, $\psi_{i,t}$ is the PSAS revenue of TPU in time period t.

The first derivative condition of profit maximization of each TPU is

$$\frac{\partial \zeta_{i,t}}{\partial \Delta P_{i,t}} = 0 \qquad \frac{\partial \psi_{i,t}}{\partial \Delta P_{i,t}} = \frac{\partial \alpha_{i,t}}{\partial \Delta P_{i,t}} \tag{6}$$

Obviously, $\partial\alpha_{i,t}/\partial\Delta P_{i,t}$ is the marginal cost of the down PSAS provided by the TPU, and the PSAS revenue $\psi_{i,t}$ of the TPU is equal to the marginal price multiplies by the peak-shaving capacity, so there is

$$\theta_{c,i,t} = \frac{\partial \psi_{i,t}}{\partial \Delta P_{i,t}} = \frac{\partial\left(\pi_{p,t} \cdot \Delta P_{i,t}\right)}{\partial \Delta P_{i,t}} = \pi_{p,t} + \frac{\partial \pi_{p,t}}{\partial \Delta P_{i,t}} \Delta P_{i,t} \tag{7}$$

$\pi_{p,t}$ is the peak-regulating marginal price and the product of it and the down-peaking power capacity $\Delta P_{i,t}$ reflects the revenue of the unit.

Solve the differential equation to get the quotation function:

$$\pi_{p,t} = \theta_{c,i,t} + \left\| \frac{\partial \pi_{p,t}}{\partial \Delta P_{i,t}} \right\| \Delta P_{i,t} \tag{8}$$

In general, market participants' quotation is based on the assumption that their quotation is equal to the marginal price of the system. Therefore, the quotation of each market participant can be approximately expressed by the formula of system marginal price. The quotation of each unit can be expressed as

$$\begin{aligned} Q_{i,t} = \pi_{p,t} &= 2a_i\beta_{\text{coal,t}}\Delta P_{i,t} - 2a_i\beta_{\text{coal,t}}P_{\text{plan},i,t} \\ &- b_i\beta_{\text{coal,t}} + \beta_{\text{elc,t}} + \left\| \frac{\partial \pi_{p,t}}{\partial \Delta P_{i,t}} \right\| \Delta P_{i,t} \end{aligned} \tag{9}$$

$Q_{i,t}$ is unit i's provided quotation of PSAS at time period t.

Consequently, we can see that the down peak shaving quotation of all units can be expressed as the sum of the marginal cost and another item.

In other words, $\partial\pi_{p,t}/\partial\Delta P_{i,t}$ is a residual demand curve slope of each unit, namely the remaining first derivative of the demand function. The residual demand curve can be derived from the market demand curve and the general supply curve of other units, while the double curve can be inferred from the past market data. We will take the function greater than zero named decision function，that is:

$$S_i(\Delta P_{i,t}) = \left\| \frac{\partial \pi_{p,t}}{\partial \Delta P_{i,t}} \right\| \tag{10}$$

For this reason, the final form of the quotation function of each unit is:

$$\begin{aligned} Q_{i,t} &= \left(2a_i\beta_{\text{coal,t}} + S_i(\Delta P_{i,t})\right)\Delta P_{i,t} \\ &- 2a_i\beta_{\text{coal,t}}P_{\text{plan},i,t} - b_i\beta_{\text{coal,t}} + \beta_{\text{elc,t}} \end{aligned} \tag{11}$$

Rules for Quotation:

At first, before the market mechanism operation, all units must report to the trading center and market regulators their own consumption of characteristic parameters (a_i , b_i, c_i and $\beta_{coal,t}$).

Then, before the trading day, each unit should report the decision function to the trading center.

Finally, at the time of settlement, market regulators can bring $\Delta P_{i,t}$ back to the above-mentioned functions $Q_{i,t}$, and judge the extent of the actual marginal cost from quotation, prevent some units to drive up prices.

2.3 Multi-objective optimization scheduling method for peak shaving auxiliary service market

In the electricity market, the main goal of the PSAS market is to maintain the balance of supply and demand at both ends of the grid, and the secondary goal is to guide the electricity market toward a healthy development based on accepting new energy as much as possible. Therefore, the first objective function is that the system has the lowest abandonment of new energy.

$$\min \Delta P_{new,t} = P_{\text{new},t,\max} - P_{\text{new},t} \tag{12}$$

Then, the second objective function is that the new energy plants purchase down PSAS at minimizing cost.

$$\min B_t = \sum_{i=1}^{N} B_{i,t}\Delta P_{i,t} \tag{13}$$

Based on this, this paper uses system power balance constraints, new energy output constraints, system reserve constraints, and quotation constraints to select units that meet the given constraints from those that are willing to participate in PSAS.

(1) System power balance constraint

$$P_t^{\text{N}} + P_t^{\text{M}} + P_{\text{new},t} = P_{\text{load},t} \tag{14}$$

(2) Constraints on the total output power of the unit

$$\begin{cases} P^{\min,\text{N}} \le P^{\min,\text{b},\text{N}} \le P_t^{\text{N}} \le P_{t,\text{plan}}^{\text{N}} \\ (\text{when} P_{t,\text{plan}}^{\text{N}} + P_t^{\text{M}} - P_{\text{load},t} + P_{\text{new},t,\max} > 0) \\ P_{t,\text{plan}}^{\text{N}} \le P_t^{\text{N}} \le P^{\max,\text{b},\text{N}} \le P^{\max,\text{N}} \\ (\text{when} P_{t,\text{plan}}^{\text{N}} + P_t^{\text{M}} - P_{\text{load},t} + P_{\text{new},t,\max} < 0) \end{cases} \tag{15}$$

(3) Constraints on the total climbing rate of the unit

When the system invokes peak-regulating auxiliary service of a certain unit, it must be a guarantee of having the ability to return to the planned output power at the next time for the unit, then the constraint is

$$\begin{cases} P_t^{\mathrm{N}} - P_{t-1}^{\mathrm{N}} \le P^{\mathrm{up,N}} \cdot \mathrm{T} \\ P_{t-1}^{\mathrm{N}} - P_t^{\mathrm{N}} \le P^{\mathrm{down,N}} \cdot \mathrm{T} \end{cases} \tag{16}$$

(4) Constraints on the climbing rate of the unit's total planned output power

$$\begin{cases} P_t^{\mathrm{N}} + P^{\mathrm{up,N}} \cdot \mathrm{T} \ge P_{t+1,\mathrm{plan}}^{\mathrm{N}} \\ P_t^{\mathrm{N}} - P^{\mathrm{down,N}} \cdot \mathrm{T} \le P_{t+1,\mathrm{plan}}^{\mathrm{N}} \end{cases} \tag{17}$$

(5) Constraints on new energy output

$$0 \le P_{\mathrm{new},t} \le P_{\mathrm{new},t,\mathrm{max}} \tag{18}$$

(6) Since TPU cannot be switched on and off frequently, the start-up and shut-down time of the unit must be restricted.

$$\begin{aligned} (T_{j,t}^{on} - T_{j,\mathrm{min}}^{on})(u_{j,t-1} - u_{j,t}) \ge 0 \\ (T_{j,t}^{off} - T_{j,\mathrm{min}}^{off})(u_{j,t} - u_{j,t-1}) \ge 0 \end{aligned} \tag{19}$$

$P_{new,t}$ is the total output value of all new energy units in the time t system, $P_{new,t,max}$ is the maximum output value of new energy units. P_t^N is the total output value of all units willing to participate in the peak regulation in the system at time t. P_t^M is the total planned output of all units in the system with no intention to participate in peak shaving at time t. $P_{load,t}$ is the System load at time t. $P^{min,N}$ is the sum of the minimum technical output values of all units in the system that are willing to participate in peak shaving. $P^{min,b,N}$ is the sum of the minimum output values reported by all the units in the system who are willing to participate in the peak shaving. $P_{t,plan}^N$ is the sum of the planned output values of all units willing to participate in the peak shaving in the system at time t. $P^{max,N}$ is the sum of the maximum technical output values of all units in the system that are willing to participate in peak shaving. $P^{up,N}$ is the sum of the maximum upward climbing rates of all units in the system willing to participate in the peak shaving. $P^{down,N}$ is the sum of the maximum downward climbing rates of all units in the system willing to participate in the peak shaving. $T_{j,t}^{on}$ is continuous operation time of thermal power unit j in time period t. $T_{j,min}^{on}$ is the minimum time for which thermal power unit j must be kept in operation. $T_{j,t}^{off}$ is the TPU j in t time consecutive stoppage time. $T_{j,min}^{off}$ is the minimum time for which TPU j must be kept out of the operation.

3 Example analysis

In this paper, we use actual operation data of a typical day of Liaoning province power grid as an example. Each bidding scheduling period is 15mins, that is, there are 96 time periods in a day.

3.1 Example analysis of original data

By analyzing the upper and lower output limits and climbing rate data of each TPU, it can be concluded that Liaoning province has the surplus peak-adjusting capacity and unit flexibility. However, the market-clearing price of both positions on that day is the highest quotation in the file, so we can infer that the enthusiasm of TPU to participate in PSAS is not high and they raise the market price jointly.

3.2 Analysis of enthusiasm for peak regulation of thermal power units

Peak-shaving capacity requirements at each time of the typical day are shown in Figure 2, under the current mechanism and dynamic mechanism, respectively.

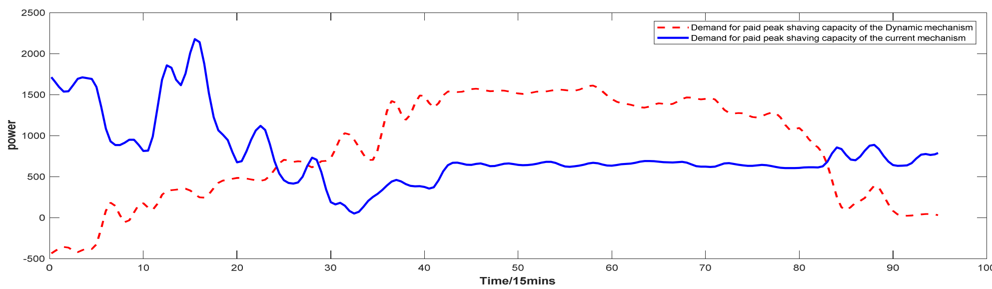

Fig2. Peak regulation capacity demand of current mechanism and dynamic mechanism

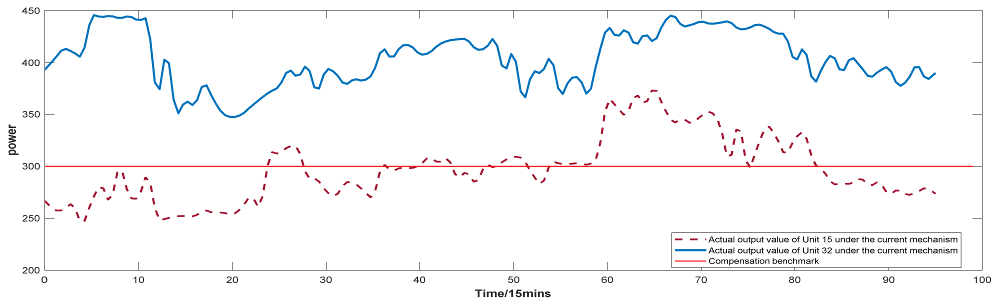

Fig3. Actual output serve of unit 32 and unit 15 under the current mechanism

The investigation discovered, unit 32, a pure condensing TPU with a capacity of 600MW, was appropriate as the representative of units that did not participate in PSAS. Figure.3 shows the output value about
unit 32 and unit 15 under the current mechanism.

Then we choose unit 15 for comparison. We learn that unit15 participated in PSAS on that day. According to the actual output value of the two units on that day, the all-day profit of the two units on that day under the current mechanism is shown in Table 1.

As can be seen from the above assumptions, if unit 32 is willing to participate in peak shaving，we regard the profit of Unit 15 as the profit of Unit 32(because the two unit parameters are the same).

When Unit 32 does not participate in PSAS, it will share 74 070.57 PSAS fees and the coal consumption cost is 852 009.8 (= 2 757 735.6-1 905 725.8), but the electricity revenue is increased by 988 628.4 (= 3 691 648.1-2 703 019.7). So, it would be more profitable not to participate in PSAS. (the difference between the revenue and entire cost is 12 006.3 (=859 841.93-847 835.63) yuan.) Therefore, the existing PSAS market mechanism makes the TPU behave low enthusiasm in peak shaving.

Table.1 Peak regulation profit analysis of unit 32 under the current mechanism

	Unit 32	Unit 15
Electricity fee income/yuan	3 691 648.1	2 703 019.7
Coal consumption cost/yuan	2 757 735.6	1 905 725.8
Peak-shaving income/yuan	0	54 501.5
Cost sharing/yuan	74 070.57	3 959.77
Full-day profit/yuan	859 841.93	847 835.63

Table.2 Peak regulation profit analysis of unit 32 under the dynamic mechanism

	Not involved in peak shaving	Participate in peak shaving
Electricity fee income/yuan	3 081 487.5	2 526 474.2
Coal consumption cost/yuan	2 220 910.2	1 768 053.7
Peak-shaving income/yuan	0	198 729.43
Cost sharing/yuan	0	0
Full-day profit/yuan	860 577.27	957 149.88

According to Table 2, under the dynamic mechanism, Unit 32's participation in PSAS will gain 96 572.61 (=957 149.88-860 577.27) yuan more than not participating in PSAS. Therefore, the dynamic mechanism can effectively improve the enthusiasm of the TPU in peak shaving.

4 Conclusion

To solve the problem of the low enthusiasm of TPU in Northeast China in participating in PSAS, this paper proposes a floating peak-shaving benchmark and quotation rules that are conducive to market supervision, thereby forming a dynamic PSAS market bidding mechanism. Besides, this paper also established a Multi-objective optimization scheduling for PSAS based on various unit operating constraints. Finally, based on the actual operating data of a typical day in the Liaoning province Power Grid, it is verified that the mechanism
can effectively improve the enthusiasm of the units in peak shaving and control the market price within a reasonable range.

At present, only TPUs are considered for participating in peak-shaving. In the future, hydropower units and other power generation participants will be considered in the market, and how to share the PSAS costs among new energy units is also an issue to be studied later.

References

1. Li Ling-Ling, Liu Yu-Wei, et al. Reducing environmental pollution and fuel consumption using optimization algorithm to develop combined cooling heating and power system operation strategies. Journal of Cleaner Production, **247**(2020).
2. Dai Cui, Cui Dai, et al. Source-load Dispatch Model for Electricity Day-ahead Market with Wind Power Penetration. In: ICEECA. Osaka, Japan. pp. 012154-(2020).
3. R. Laia, H.M.I. Pousinho, et al. Bidding Decision of Wind-thermal GenCo in Day-ahead Market. Energy Procedia, **106**:87-96(2016).

4. Xuekuan Xie, Yan Xu, et al. Multi-objective coordinated dispatch of high wind-penetrated power systems against transient instability. IET Genneration Transmission and Distribution, **14(19)**:4079-4088(2020).
5. Knueven B, Ostrowski J, et al. Exploiting identical generators in unit commitment. IEEE Transactions on Power Systems, **33(4)**: 4496-4507(2018).
6. Dun Nan Liu, Yan Zhao,et al. Regulation Right Trading Considering DSM in Shanghai Power Grid. Advanced Materials Research, **3696**:3410-3413(2015).
7. R. Garmabdari, M. Moghimi, et al. Multi-objective optimisation and planning of grid-connected cogeneration systems in presence of grid power fluctuations and energy storage dynamics. Energy, **212**(2020).
8. Hua Zhong, Zhiwei Ying, et al. Study on Monthly Trading Model of Shanghai Power Peak Regulation Market. In: CIEEC, Beijing. pp.286-291(2017).