

# ***Research on Market Strategy Optimization of Independent Energy Storage Power Station (IESPS) in Spot-Frequency Regulation Auxiliary Service Considering Photovoltaic Integration***

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**Abstract.** Driven by the "dual-carbon" strategy, the demand for flexible resources in the new power system is becoming more and more urgent. As a key adjustment means, the strategy optimization of independent energy storage power station (IESPS) participating in the power market is of great significance to improve the stability and economy of the system. The participation of photovoltaic power station is conducive to assisting energy storage to participate in frequency regulation services. A bi-level optimization model is constructed here for the collaborative decision-making problem of IESPS participating in the spot electric energy market and auxiliary service market. The upper model optimizes the charging and discharging bids and the bidding strategy of the frequency regulation auxiliary service market with the goal of maximizing the income of the energy storage power station. The lower model considers the cost of optical energy storage, conventional units and photovoltaics to achieve joint market clearing. By introducing the KKT condition, the bi-level model is transformed into a mixed integer linear programming problem, and an example is verified based on the IEEE-30 node system. The results show that the strategy can make the income of the IESPS in the frequency regulation market account for more than 75 % of the total income, shorten the payback period by over 40 % and have better economic benefits.

**Keywords:** Independent energy storage power station (IESPS), Electric energy spot market, Frequency regulation auxiliary service market, Photovoltaic integration

## **1. Introduction**

With the acceleration of the global energy transformation process, China's "Carbon peak, Carbon neutrality" goal has promoted the rapid growth of new energy installed capacity. In 2024, the new installed capacity of renewable energy power generation in China will increase by 373 million kilowatts, an increase of 23% year-on-year, accounting for 86% of the new installed capacity of electricity. However, the intermittency and volatility of new energy pose significant challenges to

grid frequency stability and supply-demand balance, and it is urgent to flexibly adjust resources to improve system resilience.

Electrochemical energy storage has developed rapidly in recent years due to its advantages of flexible configuration, charging and discharging characteristics, and millisecond response speed [1]. From the perspective of market mechanism, China's electricity market reform has been transformed from "planned electricity" to "market electricity", and the spot electricity energy market as well as the regulation auxiliary service market has been gradually improved [2]. In 2022, China has clarified that IESPS could participate as an independent entity in the electricity energy market and ancillary service markets such as frequency regulation and peak shaving. As a "flexible power source", it can replace some coal-fired power installations to participate in peak shaving and frequency regulation, and promote the low-carbon transformation of the system power structure [3].

Early studies focused on the optimization of energy storage peak-valley arbitrage and directly participated in the spot market. Reference [4] displays a new method for maximizing the profit for virtual power plants in the electricity markets via optimal power flow by controlling the power for customers participating in the demand response program and the energy storage systems in the presence of renewable energy sources. However, such studies do not consider the opportunity cost of energy storage participating in ancillary services, and there is a one-sidedness of strategy. Reference [5] addresses integrated market bidding but lacks photovoltaic coordination analysis. In recent years, multi-market collaborative optimization has gradually become a key path to improve economy [6]. Shanxi, Shandong and other places in China have carried out pilot projects of IESPS participating in the spot market. However, due to the mismatch between market segmentation and price signals, the potential of energy storage resources has not been fully released. Improving the multi-market collaborative decision-making theory has become a key step in profit maximization. By constructing a bi-level optimization model that takes the deeply coupling relationship between electricity spot market and auxiliary service market into consideration, it breaks through the limitations of single market optimization and provides a theoretical framework for the strategy design of energy storage in a complex market background and can cater for different circumstances.

## 2. IESPS participating in the electricity market

### 2.1. Electric spot-auxiliary service market

At present, China has issued a series of policies to make sure that the electricity market can operate stably. The National Energy Administration made it clear that it is of vital importance to do well in the connection between the auxiliary service market (e.g., frequency regulation and reserve) and the spot market, providing basic guidelines and norms for the operation of the electricity spot market in 2023. In 2024, for the power auxiliary service market, the National Energy Administration further improved the power price formation mechanism and improved the comprehensive adjustment ability of the power system, aiming to better play the role of the market in the allocation of power auxiliary service resources.

The spot market of electricity energy is a key component of the electricity market. It is usually composed of a day-ahead market, an intraday market and a real-time market. Some spot markets do not include the intraday market [7]. In the day-ahead market, related participants ought to predict the power generation capacity or electricity demand in advance, and submit the bids and quantity information. After centralized optimization calculation, the unit start-up and shutdown plan and the time-period electricity price are determined. The real-time balance market is based on real-time load forecasting and unit output change information to ensure real-time balance of the entire power

system and reflect the shortage of system resources. The auxiliary service market is of great significance in ensuring the safe operation of the power grid and improving the power quality, among which the frequency regulation auxiliary service market is particularly important [8]. When the power system frequency deviates from the target frequency, the grid-connected main body reduces the frequency fluctuation by adjusting the active output. The energy storage system has outstanding performance in the frequency regulation auxiliary service market can be attributed to its fast response characteristics, and can efficiently participate in the system frequency regulation. The energy storage system has fast frequency regulation speed and high precision compared to traditional units, which can better meet the high requirements of modern power system for frequency regulation resources and promote the frequency stability of power grid. The spot market and the auxiliary service market of frequency regulation are interrelated, which together constitute an important operation system of the power market and ensure the safe, stable and economic operation of the power grid as well as the power system.

Electrochemical energy storage has become one of the most commonly used energy storage technologies in the entire power system. The participation of IESPS in the electricity spot market and the frequency regulation auxiliary service market plays a vital role in the grid connection of electrochemical energy storage. Therefore, the optimization model of this paper is based on the current popular energy storage power station, which provides significant reference value for the grid connection of new energy storage equipment.

## 2.2. Basic model of IESPS participating in electricity market

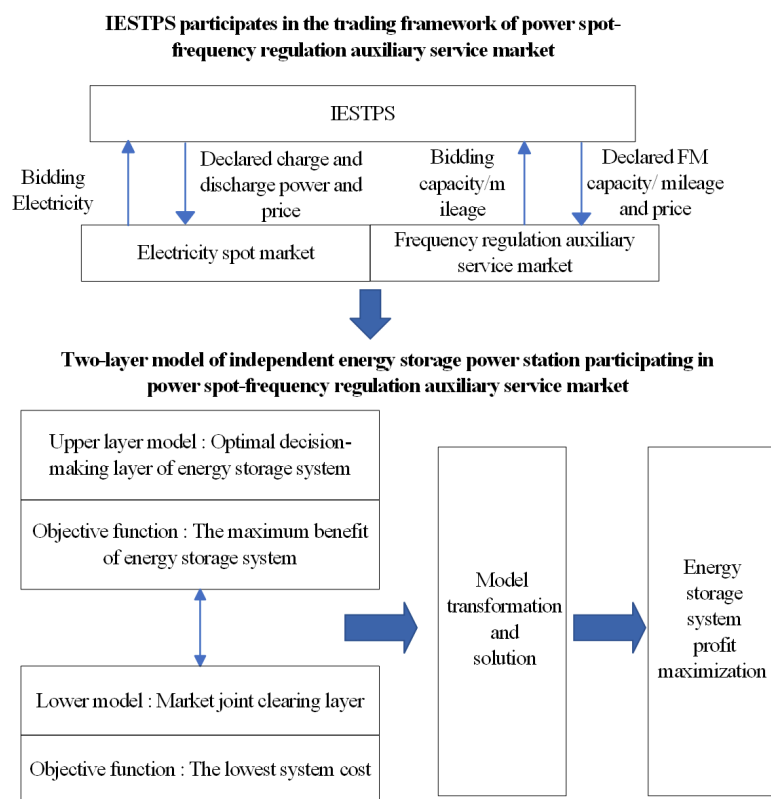


Figure 1. The trading framework and two-layer model of IESPS participating in power spot-frequency regulation auxiliary service market

Currently, people tend to divide the transaction process of the electricity market into two stages, namely the day-ahead stage as well as the real-time stage. The energy storage system declares the charging and discharging price and power of the electricity spot market, and the capacity and mileage bids of the frequency regulation market in the day-ahead stage. In the real-time stage, it executes the charging and discharging plan based on the market clearing result and provides the frequency regulation service. Under the goal of maximizing the revenue of the energy storage power station and minimizing the system power purchase cost and auxiliary service cost, this paper constructs an optimized two-layer model that combines the decision-making of the IESPS with the market clearing process to form an iterative optimization process, as shown in Figure 1.

The upper layer is the decision-making layer of the entire energy storage system, and the bid is adjusted according to the price information of the lower layer. The lower layer stands for the market clearing layer, which is re-cleared according to the new bid of the upper layer until an equilibrium state is reached. Compared with the single-layer model in [9] [10], which did not consider the real-time impact of market clearing price on leasing pricing, the bidding strategy of the two-layer model and the market clearing result match each other, which can form a better market operation scheme [11].

### 3. Decision-making model of IESPS participating in electricity spot-frequency regulation auxiliary service market transaction

#### 3.1. Transaction decision of upper energy storage power station

##### 3.1.1. Objective function

The upper layer model can be defined as the IESPS transaction decision model mainly utilized to generate the optimal bidding strategy according to the IESPS. The objective function of the upper layer model is to maximize total revenue of the two parts of the benefits obtained by the IESPS in the electric energy market and the frequency regulation market:

$$\max F_{upper} = F_1 + F_2 \quad (1)$$

Where:  $F_1$  represents the spot market income of electric energy, which is finally reflected in the low-cost charging and high-cost discharge.  $\lambda_{s,t}^E$  represents the clearing price in the node  $s$  where the energy storage is located in the  $t$  period,  $p_{s,t}^{dis}$  and  $p_{s,t}^{ch}$  represent the actual bid-winning charging and discharging power of the node  $s$  in the  $t$  period respectively:

$$F_1 = \sum_{t \in T} \sum_{s \in S} \lambda_{s,t}^E (p_{s,t}^{dis} - p_{s,t}^{ch}) \quad (2)$$

$F_2$  represents the market income of frequency regulation auxiliary service, which consists of two parts, namely, the fixed income of reserved reserve, that is, the income of frequency regulation capacity. Variable income of actual adjustment, that is, frequency regulation mileage income.  $\lambda_{s,t}^{cap}$  and  $\lambda_{s,t}^{mil}$  respectively represent the capacity clearing price and mileage clearing price of the node  $s$  where the energy storage is located in  $t$  period,  $r_{s,t}^{Ecap}$  and  $r_{s,t}^{Emil}$  respectively represent the winning frequency regulation capacity and winning frequency regulation mileage of the node  $s$  in  $t$  period :

$$F_2 = \sum_{t \in T} \sum_{s \in S} \left( \lambda_{s,t}^{cap} r_{s,t}^{Ecap} + \lambda_{s,t}^{mil} r_{s,t}^{Emil} \right) \quad (3)$$

By subdividing the income and cost items, the objective function of maximizing the income of the energy storage power station in the market environment is constructed.

### 3.1.2. Constraints

The objective function needs to consider various constraints, including physical charging and discharging capacity, market declaration price and capacity constraints.

1) Charging and discharging power constraints of the IESPS

$$\begin{cases} 0 \leq P_{s,t}^{dis} \leq \mu_{s,t}^{dis} P_{s,max}^{dis} \\ 0 \leq P_{s,t}^{ch} \leq \mu_{s,t}^{ch} P_{s,max}^{ch} \\ \alpha_{s,t}^{dis} + \alpha_{s,t}^{ch} \leq 1 \\ \alpha_{s,t}^{dis}, \alpha_{s,t}^{ch} \in [0,1] \end{cases} \quad (4)$$

Among them,  $\alpha_{s,t}^{ch}$  and  $\alpha_{s,t}^{dis}$  are the charging and discharging states of the IESPS respectively, and  $P_{s,max}^{ch}$  and  $P_{s,max}^{dis}$  stands for the maximum charging and discharging power of IESPS respectively.

2) State of charge (SOC) constraints of the energy storage system

$$\begin{cases} S_{s,t}^{SOC} = S_{s,t-1}^{SOC} + \left( \eta_{ch} P_{s,t}^{ch} - \frac{P_{s,t}^{dis}}{\eta_{dis}} \right) \\ S_{s,min}^{SOC} \leq S_{s,t}^{SOC} \leq S_{s,max}^{SOC} \end{cases} \quad (5)$$

Among them,  $S_{s,t}^{SOC}$  represents the SOC of the node s where the energy storage is located in t period,  $\eta_{ch}$  and  $\eta_{dis}$  respectively stand for the charging and discharging efficiency,  $S_{s,max}^{SOC}$  and  $S_{s,min}^{SOC}$  are the upper and lower limits of SOC respectively.

3) The declared capacity constraint of the IESPS

$$\begin{cases} 0 \leq P_{s,t}^{dis} + R_{s,t}^{Ecap} \leq P_{s,max}^{dis} \\ 0 \leq P_{s,t}^{ch} + R_{s,t}^{Ecap} \leq P_{s,max}^{ch} \\ 0 \leq R_{s,t}^{Ecap} \leq R_{s,max}^{Ecap} \\ 0 \leq R_{s,t}^{Emil} \leq R_{s,t}^{Ecap} s_{ess,s}^{mc} \end{cases} \quad (6)$$

Among them,  $R_{s,t}^{Ecap}$  and  $R_{s,t}^{Emil}$  and  $R_{s,max}^{Ecap}$  represent the declared frequency regulation capacity and the declared frequency regulation mileage of the node s where the energy storage is located at time t, respectively ;  $s_{ess,s}^{mc}$  is the frequency regulation mileage multiplier of the IESPS.

4) IESPS bids constraint

$$\begin{cases} b_{s,min}^{dis} \leq b_{s,t}^{dis} \leq b_{s,max}^{dis} \\ b_{s,min}^{ch} \leq b_{s,t}^{ch} \leq b_{s,max}^{ch} \\ b_{s,min}^{Ecap} \leq b_{s,t}^{Ecap} \leq b_{s,max}^{Ecap} \\ b_{s,min}^{Emil} \leq b_{s,t}^{Emil} \leq b_{s,max}^{Emil} \end{cases} \quad (7)$$

$b_{s,t}^{dis}$ ,  $b_{s,t}^{ch}$ ,  $b_{s,t}^{Ecap}$  and  $b_{s,t}^{Emil}$  respectively represent the discharge price, charging price, declared frequency regulation capacity price and declared frequency regulation mileage price of the node  $s$  of the energy storage in the  $t$  period in the frequency regulation market.

### 3.2. Joint clearing of the lower market

#### 3.2.1. Objective function

Aimed at realizing the efficient allocation of market resources, the lower model optimizes the coordinated operation of conventional units, IESPS and photovoltaic power stations from the perspective of system operation, for the purpose of minimizing the total cost of market joint clearing:

$$\min F_{lower} = C_E + C_G + C_{PV} \quad (8)$$

Among them,  $C_E$  is the cost of energy storage system:

$$C_E = \sum_{t \in T} \sum_{s \in S} \left( b_{s,t}^{dis} p_{s,t}^{dis} - b_{s,t}^{ch} p_{s,t}^{ch} + b_{s,t}^{Ecap} r_{s,t}^{Ecap} + b_{s,t}^{Emil} r_{s,t}^{Emil} \right) \quad (9)$$

$C_G$  represents the power generation cost of thermal power units, reflecting the marginal cost of traditional power sources,  $b_{i,t}^G$  and  $p_{i,t}^G$  represent the declared power generation price and bid-winning power of thermal power units  $i$  in the spot market during  $t$  period respectively;  $b_{i,t}^{Gcap}$ ,  $b_{i,t}^{Gmil}$ ,  $r_{i,t}^{Gcap}$  and  $r_{i,t}^{Gmil}$  respectively represent the declared frequency regulation capacity price, declared frequency regulation mileage price, winning frequency regulation capacity and winning frequency regulation mileage of thermal power unit  $i$  in the frequency regulation market:

$$C_G = \sum_{t \in T} \sum_{i \in I} \left( b_{i,t}^G p_{i,t}^G + b_{i,t}^{Gcap} r_{i,t}^{Gcap} + b_{i,t}^{Gmil} r_{i,t}^{Gmil} \right) \quad (10)$$

The  $C_{PV}$  is the photovoltaic cost.  $b_{m,t}^{PV}$  and  $b_{m,t}^{PVmil}$  respectively represent the declared electric energy price and the declared frequency regulation mileage price of the node  $m$  where the photovoltaic power station is located in the market during the  $t$  period,  $p_{m,t}^{PV}$  and  $r_{m,t}^{PVmil}$  respectively represent the bid-winning electricity quantity and the bid-winning frequency regulation mileage of the node  $m$  where the photovoltaic power station is located in the frequency regulation market during the  $t$  period:

$$C_{PV} = \sum_{t \in T} \sum_{m \in M} \left( b_{m,t}^{PV} p_{m,t}^{PV} + b_{m,t}^{PVcap} r_{m,t}^{PVcap} + b_{m,t}^{PVmil} r_{m,t}^{PVmil} \right) \quad (11)$$

The lower-level model constructs a cost minimization function in a multi-market environment by refining the lower-level costs into thermal power generation costs, energy storage power generation costs, and photovoltaic power generation costs.

### 3.2.2. Constraints

#### 1) Power balance constraint

$$\sum_{i \in I} p_{i,t}^G + \sum_{s \in S} (p_{s,t}^{dis} - p_{s,t}^{ch}) + \sum_{m \in M} p_{m,t}^{PV} - p_{L,t} = \sum_{q \in \Phi(n)} B_{nq} (\theta_{n,t} - \theta_{q,t}) : \lambda_{n,t} \quad (12)$$

$p_{L,t}$  is the system load of  $t$  period,  $\Phi(n)$  equals to the set of nodes connected with  $n$ ,  $\theta_{n,t}$  and  $\theta_{q,t}$  are the phase angles of nodes  $n$  and  $q$  at both ends of line  $l$ , and  $B_{nq}$  is the admittance of line  $l$ .  $\lambda_{n,t}$  is the dual variable, here is the marginal price of the node.

#### 2) Line transmission capacity constraints

$$-L_l \leq B_{nq} (\theta_{n,t} - \theta_{q,t}) \leq L_l : \pi_{l,t}^{min}, \pi_{l,t}^{max} \quad (13)$$

$L_l$  is the maximum transmission power limit  $\pi_{l,t}^{max}$  and  $\pi_{l,t}^{min}$  of line  $l$ , which are the dual variables of the upper and lower bounds of transmission capacity respectively.

#### 3) Frequency regulation capacity and mileage demand constraints

$$\begin{cases} \sum_{t \in T} \left( \sum_{i \in I} r_{i,t}^{Gcap} + \sum_{s \in S} r_{s,t}^{Ecap} + \sum_{m \in M} r_{m,t}^{PVcap} \right) = R_t^{SYS} : \lambda_t^{cap} \\ \sum_{t \in T} \left( \sum_{i \in I} r_{i,t}^{Gmil} + \sum_{s \in S} r_{s,t}^{Emil} + \sum_{m \in M} r_{m,t}^{PVMil} \right) = M_t^{SYS} : \lambda_t^{mil} \end{cases} \quad (14)$$

$R_t^{SYS}$  and  $M_t^{SYS}$  represent the frequency regulation capacity requirements and frequency regulation mileage requirements respectively; the dual variables  $\lambda_t^{cap}$  and  $\lambda_t^{mil}$  are the frequency regulation capacity and mileage clearing price at the moment.

## 4. Model transformation and solution

The above-mentioned two-layer model constructs an objective function structure for maximizing the profit of energy storage power stations and minimizing the market cost, and gives equality and inequality constraints, including a quadratic nonlinear programming model. KKT (Karush-Kuhn-Tucker) is a core tool for nonlinear optimization problems with equality constraints and inequality constraints [12,13]. It integrates the constraints of the original problem, the properties of the dual variables, the gradient balance and the complementary relaxation relationship, which can be regarded as the extension of the Lagrange multiplier method in the context of inequality constraints. Reference [14] applies KKT conditions to transform bi-level models for multi-market coordination. In the bi-level programming problem, if the lower optimization model satisfies the continuity and convexity, the optimal solution is the unique solution under the KKT condition, that is, the KKT condition is a sufficient condition for the optimal solution. In contrast, the stochastic programming method relies on the preset probability distribution. When the data is insufficient, the accuracy decreases and the amount of calculation increases with the scene. Game theory is difficult to solve the equilibrium solution in multi-agent scenarios, and it is difficult to incorporate system-level

constraints. Reinforcement learning is prone to strategy infeasibility under complex constraints, and it relies on a large amount of data and has poor convergence stability. There is a strong coupling relationship between the two-layer model in this paper. Therefore, KKT condition and duality theory are introduced here. The lower layer can be transformed into the constraint condition of the upper layer problem, so as to obtain a single-layer linearization problem, and the optimal solution of the model can be obtained.

However, the complementary constraint condition is still a nonlinear term. Here, the Big M Method is introduced so that it can be linearized. That is, the complementary constraint condition of  $0 \leq a - f \perp b \geq 0$  can be transformed into:

$$\begin{cases} a - f \leq M\nu \\ b \leq M(1 - \nu) \end{cases} \quad (15)$$

## 5. Example analysis

The above MILP problem can be solved by using the YALMIP toolkit and calling the GUROBI solver. This paper utilizes IEEE-30 node system to verify the effectiveness of the proposed two-layer model and solution algorithm. The system includes 6 conventional thermal power units, 41 lines and 24 load nodes. The daily load curve of the system is shown in Figure 2. All power loads are distributed proportionally at each node.

An IESPS of 20 MW / 60 MWh is added at 18 nodes, with charging and discharging efficiency set to 90 %. The maximum and minimum allowable power are 90 % and 10 % of the energy storage capacity, respectively. A photovoltaic power station is added at 8 nodes. The frequency regulation capacity bid and frequency regulation mileage bid are 12 CNY / MWh and 15 CNY / MWh, respectively. The output curve is shown in Figure 2. The frequency regulation capacity demand is 7 % of the total load in each period, and the frequency regulation mileage demand is 70 % of the total load in each period. Table 1 gives the bids information and parameters of each unit.

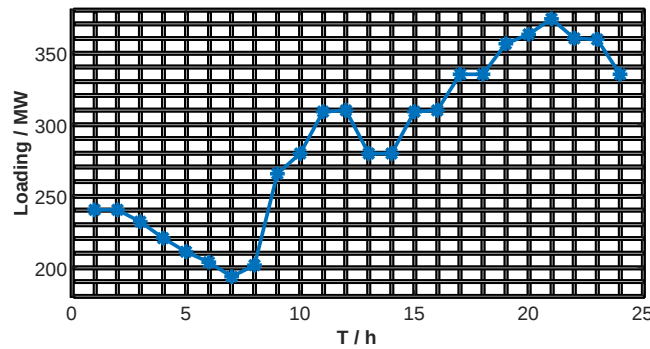


Figure 2. System daily loading curve

Table 1. Conventional thermal power unit information

| Machine set                                      | G1  | G2  | G3  | G4  | G5  | G6  |
|--------------------------------------------------|-----|-----|-----|-----|-----|-----|
| Node number                                      | 1   | 2   | 5   | 6   | 11  | 13  |
| Rated power / MW                                 | 150 | 110 | 60  | 80  | 40  | 40  |
| Power generation quote / (CNY / MWh)             | 191 | 183 | 201 | 190 | 230 | 192 |
| Frequency regulation capacity bids / (CNY / MWh) | 14  | 12  | 16  | 14  | 15  | 12  |
| Frequency regulation mileage bids / (CNY / MWh)  | 12  | 15  | 15  | 18  | 14  | 16  |
| Mileage-capacity ratio                           | 7   | 12  | 7   | 9   | 8   | 12  |

### 5.1. Electric energy spot market bidding situation

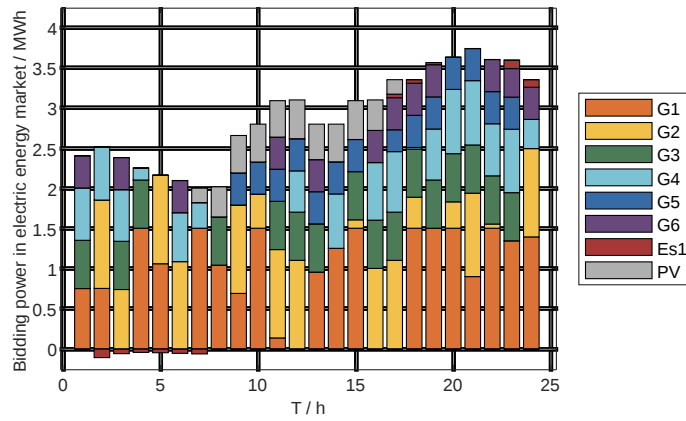


Figure 3. Winning results of the electricity market

The winning results of the electricity market are shown in Figure 3. The conventional thermal power unit undertakes the main power supply task, which shows their general position in the spot market [15]. G1 and G2 (183 CNY / MWh) are fully issued in most periods due to low bids. When the unit output is large, G4 also has a higher winning power due to the relatively low bid. The energy storage power station is charged during the low load period (2-7 o'clock) to supplement the power consumption and further put into the frequency regulation market. In the peak period (17-19 o'clock, 23-24 o'clock), the proportion of total discharge is about low, and the basic income is realized through peak-valley arbitrage.

### 5.2. Bidding situation of frequency regulation auxiliary service market

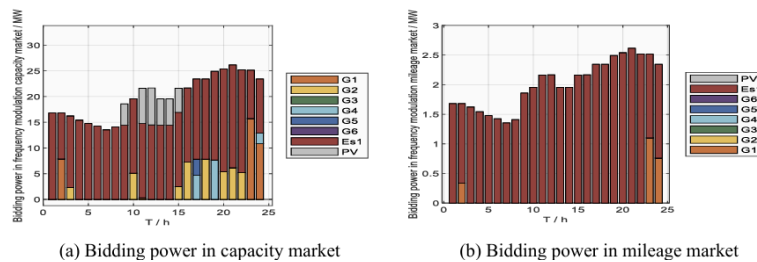


Figure 4. Bidding power in frequency regulation market

In the example, the frequency regulation ratio of the conventional unit cannot exceed 20 % of the rated power. The results of frequency regulation capacity and mileage market are shown in Figure 4.

Among them, energy storage and photovoltaic participate in frequency regulation services in coordination. By virtue of its fast response characteristics, energy storage undertakes 74 % of the frequency regulation capacity and 95 % of the frequency regulation mileage. Its mileage-capacity ratio is 15, which is much larger than that of conventional thermal power units (G1-G6 average mileage-capacity ratio is 9), providing more regulation at the same capacity. By participating in the frequency regulation, the photovoltaic power station contributes 7 % of the frequency regulation capacity, which accounts for a high proportion of output during the peak period of midday output, responds to the frequency regulation demand and complements the energy storage. The conventional unit undertakes the remaining 16 % of the frequency regulation capacity, but due to the limitation of the ramp rate, the frequency regulation mileage accounts for only 5 %.

### 5.3. Market clearing price and bidding strategy

As shown in Figure 5 (a), the clearing price of the electric energy market shows a peak-valley characteristic. The LMP reaches 600-800 CNY / MWh during the peak period (10-24 o'clock), and drops below 200 CNY / MWh during the trough period (2-6 o'clock). As shown in Figure 5 (b), the photovoltaic power station has a significant output at noon, with a maximum output of 120 MW, effectively replacing the conventional unit power generation. Normal two-layer models provide higher clearing price for the reason that they did not take photovoltaic into consideration. Affected by the fluctuation of photovoltaic output, the LMP decreases significantly during the peak period of photovoltaic output, which verifies the effect of photovoltaic on stabilizing electricity price.

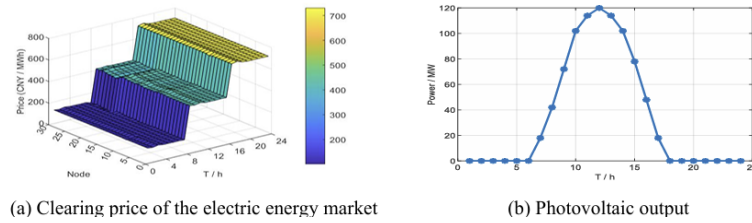


Figure 5. Influence of photovoltaic output on clearing price

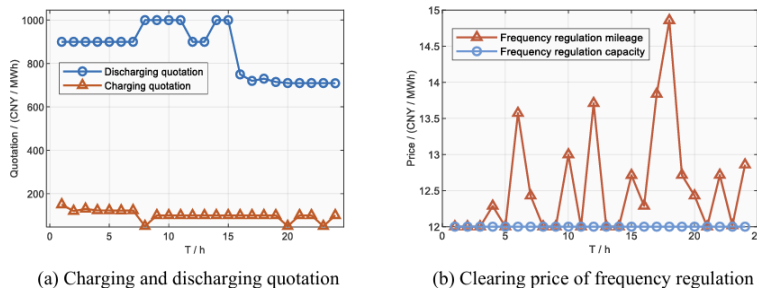


Figure 6. Bidding strategy

The charging and discharging bidding strategy of energy storage takes profit maximization as the core, and it needs to combine the bidding of other entities with their own operating characteristics to show differences in different markets, just as shown in Figure 6. The price of frequency regulation capacity is stable at 12 CNY / MWh, which is due to the stable supply and demand of the capacity market, which is deeply affected by policies and industry practices, and meets the needs of fixed

cost coverage and reasonable profit of energy storage power stations. The frequency regulation mileage price fluctuates at 12-15 CNY / MWh, because it is linked to the actual service volume: when the frequency regulation demand of the power grid is peak, the energy storage power station will raise the price according to the quotation of other subjects; in the period of flat demand, the price is reduced to ensure competitiveness. In addition, the performance of the energy storage power station, such as response speed and adjustment accuracy, will also affect its quotation in different scenarios.

#### 5.4. Profit analysis

The income structure of each subject in Table 2 shows that the energy storage power station participating in the electricity spot-frequency regulation auxiliary service market at the same time will obtain higher returns, so it has a faster return rate.

Compared with the participation of a single electric energy market, participating in multi-market coordinated distribution can have a positive effect on the revenue of the IESPS, which can maximize the sum of the benefits obtained by IESPS in the market.

Table 2. The profits of IESPS participating in different markets

| Profit / CNY                        | Spot market only   | Spot-frequency regulation market |
|-------------------------------------|--------------------|----------------------------------|
| Spot market profits                 | $3.99 \times 10^4$ | $1.78 \times 10^4$               |
| Frequency regulation market profits | -                  | $5.81 \times 10^4$               |
| Total profits                       | $3.99 \times 10^4$ | $7.59 \times 10^4$               |

#### 6. Conclusion

This paper constructs a bi-level transaction decision model for IESPS to participate in the electricity spot-frequency regulation auxiliary service market. Under the transaction mode and framework, a bi-level model of the IESPS taking part in multi-market transactions is established, and transformed into a single-layer model through KKT conditions and duality theory. The photovoltaic power station is added to the conventional IEEE-30 node system. The practical economic value of the model is verified by an example analysis, and the bidding strategy is proposed.

Compared with participating in the electric energy spot market alone, IESPS taking part in the electric energy spot-frequency regulation auxiliary service market at the same time can obtain higher economic benefits. Therefore, when formulating IESPS to participate in the market strategy, energy storage power stations should participate in the electricity spot and frequency regulation auxiliary service market at the same time. In addition, considering the characteristics of fast frequency regulation speed and high precision of energy storage system, more power distribution should be put into frequency regulation service, which not only speeds up the response speed of frequency regulation, but also achieves the effect of improving revenue, so that its revenue in the frequency regulation auxiliary market exceeds 75 % of the total revenue.

In addition, adding a PV power station to the system is instrumental in assisting the IESPS to achieve frequency regulation services in the peak period of electricity consumption, while alleviating the pressure on thermal power units in the electricity spot market.

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