# Optimal Configuration of the User Side Energy Storage With Multiple Values Considering Frequency Regulation

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***Abstract*—Energy storage has the ability of fast and flexible bi-directional power regulation, which can change the traditional power system's attribute of instant balance. At present, the energy storage application is still in an initial stage, so it is necessary to study how to get the best out of the multiple values of energy storage in the power system to improve its economy. This paper studies an optimal configuration method of the user-side energy storage with multiple values considering frequency regulation. Firstly, the load characteristics are introduced, and the feasibility of energy storage to play multiple values is illustrated. Secondly, according to the frequency regulation market mechanism, the role of the thermal generating unit and the energy storage in the process of frequency regulation is quantified, and the revenue distribution mechanism is designed. Then, the optimal configuration model of the user side energy storage with multiple values is established. Finally, a case study shows that the method proposed in this paper can improve the economy of the energy storage configuration.**

***Keywords—energy storage; user-side; multiple values; revenue distribution; frequency regulation; optimal configuration***

## I. Introduction

In the trend of large-scale renewable energy generation connected to the power grid, energy storage can provide a stronger regulation ability for the energy balance of the power grid [1]. With the maturity of the energy storage technologies, China's energy storage industry is developing rapidly, and the energy storage on the grid side has achieved good effects in improving power system reliability [2]. However, at the current stage, the application of the energy storage in the user-side still has the problems of high cost, low utilization rate and few benefit sources [3]. Thus, the multiple values of energy storage, including peak shaving and frequency regulation, should be fully evaluated in the configuration of the energy storage to improve its economic benefits [4].

So far, quite a few researchers have studied the optimal configuration of the user-side energy storage. Some researchers have calculated the life-cycle cost of the energy storage, but have not built a detailed model for the benefit of the energy storage, and the charge and discharge strategy was determined only according to the time of use (TOU) tariff [5]. Others have researched the economics of the energy storage for peak load shaving or demand management [6]. With the continuous improvement of the market mechanism of frequency regulation auxiliary service, it is possible for the energy storage to involve in frequency regulation and obtain benefits from it. And some researchers have researched on the performance and economy of the energy storage auxiliary thermal power unit in frequency regulation [7]. These results are not applicable to the user side energy storage, because the revenue distribution mechanism between the thermal generating unit and the energy storage has not been studied.

Under the current electricity market mechanism, it is feasible for the user side energy storage to play two roles of peak load shaving and frequency regulation. At present, this point has not been considered in the configuration of the energy storage, and the multiple values of the energy storage has not been fully developed. Furthermore, the load characteristics are closely related to the benefits of the energy storage in the user side, which should also be considered in the configuration of the energy storage.

Based on the above research, this paper proposes an optimal configuration method of the user-side energy storage with multiple values considering frequency regulation. The rest of this article is organized as follows: Firstly, the load characteristics and the feasibility of energy storage to play multiple values are introduced. Secondly, the revenue distribution mechanism of the thermal generating unit and the energy storage in the process of frequency regulation is designed. Then, the optimal configuration model of the energy storage with multiple values is established. Finally, a specific case is tested to verify the validity of the proposed method. The main contributions of this article are as follows:

1) A reasonable revenue distribution mechanism of the thermal generating unit and the energy storage in the process of frequency regulation;

2) An optimal configuration method of the user-side energy storage with multiple values considering frequency regulation, which can improve the application benefits of the user side energy storage.

## II. Load Characteristics

Load characteristics have great effects on the revenue source of the user-side energy storage. For example, when the distribution of load power in a day is similar to the distribution of TOU price, energy storage can generate income through peak shaving and valley filling. Considering a longer time scale, if the load distribution has a strong heterogeneity, the revenue can be obtained by using energy storage for demand management. Affected by people's work and rest rules and the relationship between the demand and the market supply, the production intensity of industrial users in different periods of a year is different, which leads to the non-uniformity of their electricity consumption in time. Fig. 1 shows the typical weekly load curve of a wharf microgrid, with an interval of 30 minutes between two time points.

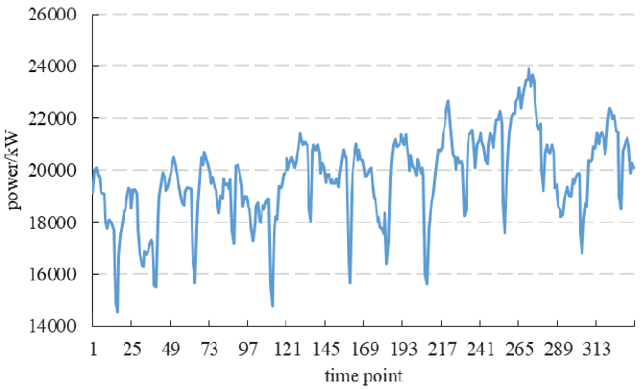


Fig. 1. Typical weekly load of a wharf microgrid

As can be seen from Fig. 1, the peak of the user's load occurs only in a short period of a week. At present, most areas implement the two-part tariff for industrial users [8], that is, calculate the tariff according to the basic tariff and the electricity tariff:

$$C_{\mathrm{m}} = \sum_{i=1}^{m}\sum_{t=1}^{n} c_t P_{i,t} T + c_{\mathrm{b}} P_{\max} \tag{1}$$

Where $C_{\mathrm{m}}$ is the monthly electric bill of the user; $m$ is the number of days in the month; $i$ is the day number of the month; $n$ is the number of periods in a day; $t$ is the time period number in a day; $c_t$ is the TOU price; $P_{i,t}$ is the power demand in period $t$; $c_b$ is the basic tariff; $T$ is the duration of the unit period of time; $P_{\max}$ is user's maximum electricity demand in the month.

In order to reduce the basic electricity tariff, a feasible method is to install energy storage in the microgrid for peak shaving to reduce the maximum power demand of the wharf. But the configuration of energy storage for this purpose alone may not be the most economical. Fig. 2 shows the relationship between the user's maximum demand and the maximum continuous discharge capacity of the energy storage.

From Fig. 2 it appears that with the decrease of the maximum demand, the required energy storage capacity will increase in a super linear trend. Therefore, if the user side energy storage is only used for peak shaving, with the increase of the energy storage capacity, the revenue of per unit capacity will continue to decrease, which limits the large-scale application of the energy storage. Fig. 3 shows the relationship between the peak shaving time proportion and the user's maximum demand.

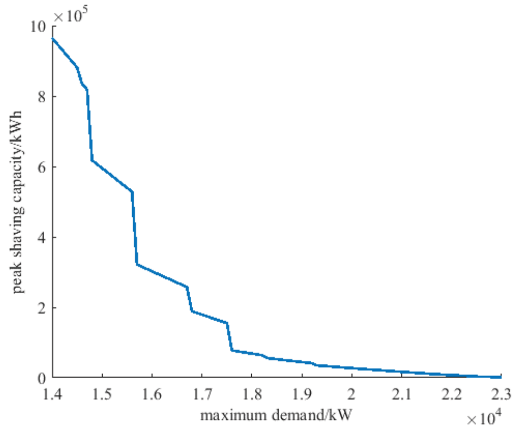


Fig. 2. Maximum peak shaving capacity

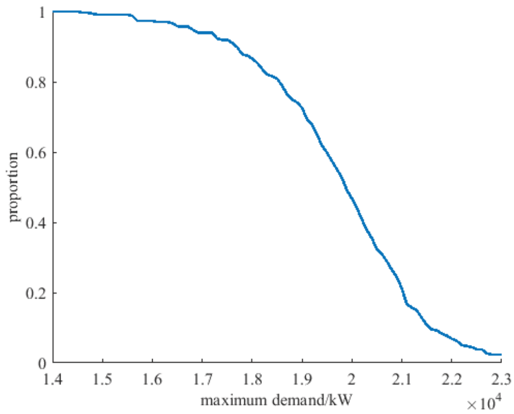


Fig. 3. Peak shaving time proportion

As can be seen from Fig. 3, when the expected maximum demand is above 20MW, the energy storage will be required to discharge for peak shaving in less than 50% of the time. Hence, the energy storage can be optimized for more features like frequency regulation in the remaining of the time to generate more benefits.

The above analysis of load characteristics shows that it is feasible for energy storage on the user side to play multiple values, such as peak load shaving and frequency regulation.

## III. Revenue Distribution of Frequency Regulation

Automatic generation control (AGC) is an important real-time control function in the operation of the power grid. Its purpose is to match the generation output and load power of the whole system and keep the system frequency as rated value. The traditional thermal power unit has a slow climbing speed and a long response time, which is not conducive to ensuring the power quality of the power system. Given that the energy storage has the ability of quick response but limited storage capacity, this paper considers the energy storage cooperating with a thermal power unit in frequency regulation.

### *A. Revenue of frequency regulation*

The benefits of the energy storage assisting AGC of the thermal generating unit include the increase of AGC compensation cost and the decrease of assessment cost. According to the market mechanism of frequency regulation auxiliary service in Guangdong province [9], the AGC compensation cost is divided into the frequency regulation mileage compensation and the AGC capacity compensation. The calculation equation of the monthly frequency regulation mileage compensation is as follows:

$$R_{\mathrm{m1}} = \sum_{i=1}^{m} D_i Q_i K_i \tag{2}$$

Where $R_{\mathrm{m1}}$ is the monthly frequency regulation mileage compensation cost; $D_i$ is the frequency regulation mileage of the generating unit on the $i$th day; $Q_i$ is the mileage settlement price of the $i$th day; $K_i$ is the frequency regulation comprehensive performance index of the power generation unit on the $i$th day.

The calculation formula of the frequency regulation comprehensive performance index is as follows:

$$K_i = \frac{1}{N}\sum_{j=1}^{N} 0.25\times(2K_{1,j} + K_{2,j} + K_{3,j}) \tag{3}$$

Where $N$ is the number of AGC instructions in a day; $j$ is the number of the instruction; $K_{1,j}$ is the regulation speed; $K_{2,j}$ is the response time; $K_{3,j}$ is the regulation precision.

$$K_{1,j} = \frac{v_j}{v} \tag{4}$$

$$K_{2,j} = 1 - \frac{d_j}{5\,\mathrm{min}} \tag{5}$$

$$K_{3,j} = 1 - \frac{e_j}{e_{\mathrm{lim}}} \tag{6}$$

Where $v_j$ is the measured speed of the generating unit; $v$ is the average standard regulation speed of AGC power generation units in frequency regulation area; $d_j$ is the time delay in response to the AGC instruction; $e_j$ is the deviation between the control value and the actual output; $e_{\mathrm{lim}}$ is the permissible error of regulation.

The calculation formula of the monthly AGC capacity compensation of the power generation unit is as follows:

$$R_{\mathrm{m2}} = \sum_{i=1}^{m} C_i T_i s \tag{7}$$

Where $R_{\mathrm{m2}}$ is the monthly AGC capacity compensation cost; $C_i$ is the AGC capacity of the generating unit on the $i$th day; $T_i$ is the frequency regulation service duration of the generating unit on the $i$th day; $s$ is the AGC capacity compensation price.

### *B. Revenue distribution mechanism*

According to the frequency regulation market mechanism, this section quantifies the role of the thermal generating unit and the energy storage in the process of frequency regulation, and designs the revenue distribution mechanism of them.

The cooperative game is a widely used cost allocation method. In this method, the cost of a single member is directly allocated to the member, and then the revenue from cooperation is allocated to each member according to certain principles [10]. In the case of the energy storage assisting AGC of the thermal generating unit, the thermal generating unit plays a major role and the energy storage plays an auxiliary role. The status of the two is not equal, so the cost allocation method based on the cooperative game cannot be applied directly. A basic principle is that after the energy storage participates in frequency regulation, the revenue of both the energy storage and the thermal generating unit should increase. Suppose that the regulation speed of the thermal generating unit and the energy storage is as follows:

$$K_{1\mathrm{ts},j} = \frac{P_{\mathrm{E},j} - P_{\mathrm{S},j}}{(T_{\mathrm{E},j} - T_{\mathrm{S},j})v} \tag{8}$$

Where $K_{1\mathrm{ts},j}$ is the regulation speed of the thermal generating unit and the energy storage; $P_{\mathrm{S},j}$ and $P_{\mathrm{E},j}$ are the starting power and the ending power respectively; $T_{\mathrm{S},j}$ and $T_{\mathrm{E},j}$ are the start time and the end time respectively.

Suppose that the response time of the thermal generating unit and the energy storage is as follows:

$$K_{2\mathrm{ts},j} = 1 - \frac{d_{\mathrm{s},j}}{5\,\mathrm{min}} \tag{9}$$

Where $K_{2\mathrm{ts},j}$ is the response time of the thermal generating unit and the energy storage; $d_{\mathrm{s},j}$ is the time delay of the energy storage which combined with the thermal generating unit in response to the AGC instruction.

According to the calculation formula of the regulation speed, the revenue of it is distributed linearly according to the regulation speed of the thermal generating unit and the energy storage. Therefore, the regulation speed index of the energy storage can be defined as follows:

$$K_{1\mathrm{s},j} = K_{1\mathrm{ts},j} - K_{1,j} \tag{10}$$

The energy storage has the ability of speedy response, hence when the energy storage assisting AGC of the thermal generating unit, the response time index is mainly achieved by the energy storage. Given that the revenue of the thermal generating unit should increase after the energy storage participates in the frequency regulation, the response time index of the energy storage is defined as follows:

$$K_{2\mathrm{s},j} = K_{2\mathrm{ts},j} - K_{2,j} \tag{11}$$

Suppose that the regulation precision index of the thermal generating unit and the energy storage is $K_{3\mathrm{ts},j}$. Considering that the rated power of the energy storage is relatively small, the improvement of regulation precision index is not entirely the contribution of the energy storage.

When the energy storage responds to AGC command independently, its regulation precision is as follows:

$$K_{3\mathrm{si},j}=\begin{cases}1-\dfrac{e_{\mathrm{s},j}}{e_{\lim}}, & \Delta P_j\le P_{\mathrm{s}}\\ \max\left(1-\dfrac{e_{\mathrm{s},j}}{e_{\lim}},1-\dfrac{\left|\Delta P_j-P_{\mathrm{s}}\right|}{P_{\mathrm{t}}e_{\lim}}\right), & \Delta P_j>P_{\mathrm{s}}\end{cases} \tag{12}$$

Where $K_{3\mathrm{si},j}$ is the regulation precision index of the energy storage responding to AGC independently; $e_{\mathrm{s},j}$ is the deviation value between the actual output of the energy storage and the control command value; $\Delta P_j$ is the deviation between the control value and the current output of the thermal generating unit; $P_{\mathrm{s}}$ is the rated power of the energy storage; $P_{\mathrm{t}}$ is the rated power of the thermal generating unit.

In the light of formula (12), the regulation precision index of the energy storage is defined as follows:

$$K_{3\mathrm{s},j}=\begin{cases}K_{3\mathrm{ts},j}-K_{3,j}, & \dfrac{\Delta P_j-P_{\mathrm{s}}}{P_{\mathrm{t}}}\le\dfrac{e_j}{e_{\lim}}\\ \dfrac{2e_j}{e_{\lim}}\dfrac{1-\dfrac{e_j}{e_{\lim}}}{2-\dfrac{e_j}{e_{\lim}}-\dfrac{\Delta P_j-P_{\mathrm{s}}}{P_{\mathrm{t}}e_{\lim}}}, & \dfrac{\Delta P_j-P_{\mathrm{s}}}{P_{\mathrm{t}}}>\dfrac{e_j}{e_{\lim}}\end{cases} \tag{13}$$

According to the above index calculation method, the frequency regulation comprehensive performance index of the energy storage is as follows:

$$K_{\mathrm{s},i}=\frac{1}{N}\sum_{j=1}^{N}0.25\times(2K_{1\mathrm{s},j}+K_{2\mathrm{s},j}+K_{3\mathrm{s},j}) \tag{14}$$

Where $K_{\mathrm{s},i}$ is the frequency regulation comprehensive performance index of the energy storage on the $i$th day.

The AGC capacity refers to the sum of up regulatable capacity and down regulatable capacity within 5 minutes at the current output point of the power generation unit. Due to the large power ramp rate of energy storage, its AGC capacity is approximately equal to $2P_{\mathrm{s}}$.

The revenue of the energy storage from the frequency regulation market is as follows:

$$R_{\mathrm{ms}}=\sum_{i=1}^{m}\left(D_iQ_iK_{\mathrm{s},i}+2P_{\mathrm{s}}NT_is\right) \tag{15}$$

Where $R_{\mathrm{ms}}$ is the monthly revenue of the energy storage assisting AGC of the thermal power unit.

## IV. Optimal Configuration Model of the User Side Energy Storage

### A. Life-cycle cost of the energy storage

The cost of the energy storage system in the whole life-cycle primarily includes the initial investment cost, degradation cost and maintenance cost. The initial investment cost is a one-time fixed capital invested in the initial phase of the project, which is determined by the rated power and capacity of the energy storage battery. The expression of the initial investment cost is as follows:

$$C_{\mathrm{init}}=c_{\mathrm{pcs}}P_{\mathrm{s}}+c_{\mathrm{bat}}E_{\mathrm{s}} \tag{16}$$

Where $C_{\mathrm{init}}$ is the initial investment costs of the energy storage; $c_{\mathrm{pcs}}$ is the unit power cost; $c_{\mathrm{bat}}$ is the unit capacity cost; $E_{\mathrm{s}}$ is the rated capacity of the energy storage.

When the life-cycle of the energy storage is less than the actual project cycle, the energy storage needs to be replaced. The degradation cost refers to the capital spent to replace battery energy storage equipment in the whole life-cycle [11]. The expression of the degradation cost is as follows:

$$C_{\mathrm{rep}}=\sum_{k=1}^{l}c_{\mathrm{bat}}E_{\mathrm{s}}(1+r)^{-kT_{\mathrm{life}}} \tag{17}$$

Where $C_{\mathrm{rep}}$ is the degradation cost of energy storage; $k$ is the number of replacement; $l$ is the total number of replacement in the energy storage's life-cycle; $r$ is the discount rate; $T_{\mathrm{life}}$ is the equivalent cycle life of energy storage.

The annual cost of the initial investment and later replacement of energy storage is as follows:

$$C_{\mathrm{inv}}=\frac{1}{T_{\mathrm{LCC}}}\left(C_{\mathrm{init}}+C_{\mathrm{rep}}\right) \tag{18}$$

Where $C_{\mathrm{inv}}$ is the annual cost of the initial investment and later replacement of the energy storage; $T_{\mathrm{LCC}}$ is the life-cycle of the energy storage, $T_{\mathrm{LCC}}=T_{\mathrm{life}}(l+1)$.

The maintenance cost refers to the dynamic cost to ensure the energy storage system's normal operation within the service life, which usually includes the fixed part determined by the power conversion system and the variable part determined by the discharge and charge capacity of the battery energy storage.

$$C_{\mathrm{om}}=\frac{1}{T_{\mathrm{LCC}}}\left(c_{\mathrm{Pom}}P_{\mathrm{s}}\frac{(1+r)^{T_{\mathrm{LCC}}-1}}{r(1+r)^{T_{\mathrm{LCC}}}}+\sum_{u=1}^{T_{\mathrm{LCC}}}c_{\mathrm{Eom}}W_u(1+r)^{-u}\right) \tag{19}$$

Where $C_{\mathrm{om}}$ is the annual maintenance cost of the battery energy storage; $c_{\mathrm{Pom}}$ is the unit power maintenance cost; $u$ is the number of operating years of the battery energy storage; $c_{\mathrm{Eom}}$ is the unit capacity maintenance cost; $W_u$ is the charge and discharge capacity of the battery energy storage in the $u$th year.

### B. Optimal configuration model

This section establishes the optimal configuration model of the user side energy storage with multiple values including peak shaving and valley filling, demand side management and frequency regulation. The objective function is to maximize the net profit of the battery energy storage.

$$\max\left(\sum_{p=1}^{12}\left(R_{\mathrm{ms},y,p}-C_{\mathrm{m},y,p}\right)-C_{\mathrm{inv}}-C_{\mathrm{om}}\right) \tag{20}$$

Where $R_{\mathrm{ms},y,p}$ is the revenue of the energy storage in the $p$th month of the $y$th year; $C_{\mathrm{m},y,p}$ is the electric bill of the user in the $p$th month of the $y$th year.

The constraints include the user demand constraint, energy storage output and state of charge (SOC) constraints.

$$P_{i,t} \le P_{\max} \tag{21}$$

$$-P_s \le P_{s,i,t} \le P_s \tag{22}$$

$$S_{\min} \le S_{i,t} \le S_{\max} \tag{23}$$

Where $P_{s,i,t}$ is the power of the battery energy storage in period $t$ on the $i$th day; $S_{i,t}$ is the SOC of the battery energy storage in period $t$ on the $i$th day; $S_{\max}$ and $S_{\min}$ are the maximum and minimum SOC of the battery energy storage respectively.

### C. Solving method

The above battery energy storage configuration model is a bi-level optimization model. The upper layer optimization aims at the maximization of energy storage revenue, and takes the rated capacity and power of energy storage as variables to optimize. The lower level optimization uses the rated capacity and power of energy storage obtained from the upper level optimization, and takes the output of energy storage as variables to optimize the operation and calculate the maximum revenue of the energy storage.

Using particle swarm optimization (PSO) to solve the upper layer optimization problem, and using CPLEX optimization software to solve the lower layer optimization problem, the specific steps are as follows:

(1) The position of each particle is a two-dimensional vector representing the rated capacity and power of energy storage. Initializing the particle swarm, including the population size, the velocity and position of each particle.

(2) Based on the particle position value, using CPLEX optimization software to solve the lower layer optimization problem, and get the maximum revenue of the energy storage, that is, the fitness value of particles.

(3) For each particle, taking the larger of its fitness value and individual extremum as the new individual extremum.

(4) Comparing the individual extremum of each particle with the global extremum, and taking the larger value as the new global extremum.

(5) Updating the velocity and position of all particles.

(6) Determining whether the algorithm terminative condition is met: If yes, the energy storage configuration result is obtained; otherwise, return to step (2).

## V. Case Analysis

This article uses the above wharf as an example to analyze the proposed energy storage configuration method. The energy storage assists AGC of a 300MW thermal generating unit. The AGC historical data of the thermal generating unit for one year is taken as the data base of the planning.

The constants required for the energy storage optimal configuration are as follows: $T$=30min, $n$=48, $N$=17280, $c_b$=40 yuan/(kW·m) , $c_{bat}$=2688 yuan/kWh, $v$=4.5 MW/min, $e_{lim}$=4.5 MW, $T_{LCC}$=10, $s$=12yuan/MWh, $c_{Pom}$=70yuan/kW, $c_{pcs}$=1610 yuan/kW, $c_{Eom}$=100 yuan/MWh, $r$=8%, $S_{min}$=0.1, $S_{max}$=0.9, the cycle number of the energy storage is 3000. The TOU price implemented in Guangzhou is as follows: In 14:00-17:00 and 19:00-22:00, the electricity power price is 1.1573 yuan/kWh; In 00:00-08:00, the electricity power price is 0.3507 yuan/kWh; In 08: 00-14: 00, 17: 00-19: 00 and 22: 00-24: 00, the electricity power price is 0.7014 yuan/kWh.

Substituting the above constants into the proposed optimal configuration model of the battery energy storage. Using PSO to solve the upper layer optimization problem, and using CPLEX optimization software to solve the lower layer optimization problem. The PSO population size is 100, the maximum iteration number is 100, the learning factor is 1.5, the maximum and minimum inertia weights are 0.8 and 0.4 respectively, the maximum particle position is 30, the maximum and minimum velocities are 10 and -10 respectively.

The optimal rated capacity and power of the battery energy storage are 11.4794 MW and 7.5145 MWh respectively, and the optimal revenue of the battery energy storage in its whole life-cycle is $3.5107 \times 10^7$ yuan. Fig. 4 shows the response of the thermal generating unit to AGC independently, and the response of the thermal power unit assisted by the battery energy storage to AGC during a certain period of time.

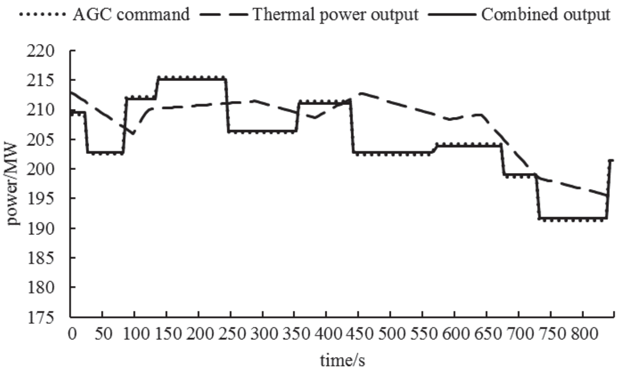


Fig. 4. Combined output of the energy storage and the thermal unit

As can be seen from Fig. 4, the combined output after adding the energy storage system is more close to the AGC command value, which significantly improves the frequency regulation performance of the power generation unit.

After the installation of the battery energy storage, the maximum power demand of the user is reduced by 1.252 MW.

When the energy storage is not considered to involve in the frequency regulation, the optimal revenue of the battery energy storage configuration is $1.9123 \times 10^7$ yuan. Therefore, according to the load characteristics and the electricity market mechanism, considering the multiple values of the energy storage to make full use of it can significantly improve economic benefits of the user.

## VI. Conclusion

This paper proposes an optimal configuration method of the user side energy storage with multiple values considering frequency regulation. Based on the analysis of load characteristics and the current electricity market mechanism, the functions of energy storage are determined in the planning stage, including peak shaving and valley filling, demand management and frequency modulation. The case study shows that getting the best out of the multiple values of the energy storage can effectively improve its economy. Our future work will focus on studying the joint frequency regulation method of the user side energy storage and the thermal power plant considering communication delay and communication failure.

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