An Energy Storage Capacity Optimization Method for Aggregator Based on Users’ Participation Evaluation

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Abstract. With the increase of the installed capacity of electrochemical batteries, how to maximize the benefit of large-scale energy storage system (ESS) has become an urgent problem. Therefore, this paper intends to establish an optimization model of aggregator based on users’ participation evaluation. Firstly, the idea of hierarchical capacity optimization for ESS is introduced, and the charging and discharging power distribution of distributed energy storage system (DESS) is evaluated. Then, based on the price-based demand response model, a DESS aggregation model based on herd psychology is established to evaluate the functional relationship between subsidy and participation. Finally, the capacity optimization model of aggregator participating in peak load regulation based on users’ participation evaluation is established. An example is given to verify the effectiveness of the proposed model.

1. Introduction
With the "dual carbon" target proposed by the Chinese government, the installed capacity of renewable energy (RE) will be in explosive growth. At the same time, local governments issued corresponding policies to require RE installation must be equipped with a certain capacity of ESS. The ESS has the characteristics of fast response speed, strong power throughput capacity and unrestricted site selection[1]. It has a good application prospect in absorbing RE and guaranteeing power supply. However, due to the relatively high investment cost at present, the economic benefit is not obvious[2]. Therefore, it is necessary to study the optimal allocation of ESS capacity and explore the economic benefits under large-scale ESS installation.

10kV

0.4kV
DESS1 DESSm
load
ESS aggregator

Figure 1. The typical wiring diagram of the hierarchical ESS
The hierarchical ESS mainly includes centralized energy storage (CESS) on the grid side, DESS on the user side and energy management system (EMS). The typical wiring diagram of the hierarchical ESS is shown in figure 1. The CESS is generally installed on the grid side, with relatively large capacity and long discharge time. It is directly dispatched by the State Grid and mainly solves prominent problems such as grid-side peak load regulation and frequency modulation. DESS is generally installed on the user side, which has a relatively small capacity but a large quantity. It can play the role of arbitraging between peak and valley electricity prices and absorbing RE. Literature[3] has analyzed the control strategy of hierarchical ESS for demand response through autonomous coordination under different scenarios. Literature[4] realizes the aggregation of DESS through aggregators under the hierarchical architecture can participate in the auxiliary service of power grid as an independent operator.

Inspired by the reference[4], this paper focuses on the optimization of the aggregator's ESS capacity based on users' participation evaluation. In the hierarchical architecture, the DESS power and the users' participation are first evaluated to calculate the aggregator's aggregation capacity. Then, based on the price-based demand response model, a DESS aggregation model based on herd psychology is established to evaluate the functional relationship between subsidies and participation. Finally, the capacity optimization model of aggregator's ESS participating in peak load regulation based on users' participation evaluation is established. An example is given to verify the effectiveness of the proposed model.

2. DESS power evaluation

There is no doubt that users will choose to discharge in the period of peak electricity price and charge in the period of valley electricity price, so that they can obtain higher income. It is assumed that the peak electricity price period is continuous \([T_s, T_e]\), but the start time of users' discharge in this period is random to a certain extent. According to the central limit theory of probability theory, the start time of discharge can be considered to follow a normal distribution [5], and its expression is as follows:

\[
f(t) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left( -\frac{(t-\mu)^2}{2\sigma^2} \right)
\]

where \(t\) represents the start time of discharge; \(\mu\) and \(\sigma\) represent the mean and standard deviation of the initial discharge time, respectively.

Monte Carlo simulation sampling method is used to generate the initial time series of user discharge, and then the power distribution at each moment is calculated, which can evaluate the discharge power of DESS. The evaluation method is as follows:

Since the start time of discharge is random and the discharge will last for a period of time (typically 2h), the total discharge power at any time \(t\) is the result of the superposition of the stored energy power that starts discharging at this moment and the stored energy power that has started discharging but continues in the discharge process. For the sake of illustration, it is assumed that the DESS capacity of each user is similar, which is \(P_{ESS}/E_{ESS}\), and the discharge rate and discharge depth are the same. Therefore, the discharge time of each DESS is the same, set as \(T_0\). Then, the total discharge power of stored energy at time \(t\), \(P_o\) can be expressed as:

\[
P_{d, j} = \begin{cases} 
\sum_{j=1}^{i} P_{d,j}, & t - i \leq T_0 \\
\sum_{j=1}^{i} P_{d,j}, & t - i > T_0 
\end{cases}
\]

\[P_{d,j} = MP_{ESS} \int_{t+i}^{t+1} f(t) dt\]

where \(M\) represents the number of users; \(P_{d,j}\) represents the power at any moment when user \(j\) starts discharging; \(f(t)\) represents the probability density function of the initial discharge time; \(i\) denotes the critical discharge time.
3. DESS aggregation model based on herd psychology

3.1. Price-based demand response model
At present, the price-based demand response model is mainly modeled and analyzed based on the linear relationship\[6\], and the functional relationship between response power $P_L$ and subsidy $\rho$ is:

$$P_L = a\rho + b \quad (3)$$

where $a$ and $b$ are price elasticity coefficients.

In this paper, based on the demand response model, a DESS aggregation participation model is established to evaluate the aggregation capacity. Without loss of generality, we stipulate that: when the subsidy price is lower than the critical incentive level $\rho_0$, the participation is 0; When the subsidy price exceeds the saturation incentive level $\rho_1$, the participation is 100%. When the subsidy price is between $\rho_0$ and $\rho_1$, the participation degree approximately satisfies a linear relationship. To sum up, the functional relationship between participation $F(\rho)$ and subsidy price $\rho$ can be expressed as:

$$F(\rho) = \begin{cases} 0, & \rho \leq \rho_o \\ \frac{1}{\rho_1 - \rho_0} (\rho - \rho_o), & \rho_o \leq \rho \leq \rho_i \\ 1, & \rho \geq \rho_i \end{cases} \quad (4)$$

According to the knowledge of probability theory, $F(\rho)$ is the joint distribution function of participation. Therefore, the probability density function $F(\rho)$ of participation can be solved by taking the derivative of $F(\rho)$, and the function relation is:

$$f(\rho) = \begin{cases} \frac{1}{\rho_1 - \rho_o}, & \rho_o \leq \rho \leq \rho_i \\ 0, & \text{else} \end{cases} \quad (5)$$

where $f(\rho)$ is the probability density function of participation. Here, it can be defined as the subjective economic satisfaction of users, representing users’ satisfaction with different subsidy price.

3.2. DESS participation model based on herd psychology
In fact, users’ participation is not only related to the subsidy price, because when users choose whether to participate in response, they not only have to consider their own will, but also will be influenced by the people around them, and users will have an obvious herd psychology. Herd psychology brings some uncertainty to the above model. Therefore, based on the above model and considering user conformity psychology, this paper studies the functional relationship between participation and subsidies under the group conformity learning mechanism.

When the subsidy price $\rho$ is lower than $(\rho_0 + \rho_1)/2$, the conformity is negative. When the subsidy price $\rho$ is higher than $(\rho_0 + \rho_1)/2$, the conformity is positive. The functional relationship can be expressed as:

$$F'(\rho) = \begin{cases} F(\rho) - \Delta F(\rho), & \rho_o \leq \rho \leq \frac{\rho_o + \rho_i}{2} \\ F(\rho) + \Delta F(\rho), & \frac{\rho_o + \rho_i}{2} < \rho \leq \rho_i \end{cases} \quad (6)$$

Where $F'(\rho)$, $F(\rho)$ and $\Delta F(\rho)$ represent the actual participation based on the herd mentality, the participation based on the conventional demand response and the change amount of the participation considering the herd mentality, respectively.

Based on the research results of literature [7-8], a mathematical model of dynamic evolution of user economic satisfaction based on conformity psychology is established:
\[ \lambda = \lambda_0 \exp(-F(\rho) \ln \lambda_0) \]  
\[ x'_i = (1 - \lambda)x_i + \lambda x_e \]  
\[ x_e = \frac{\sum x_i f_i}{\sum i f_i} \]  

where \( \lambda \) represents the dynamic conformity coefficient under the conformity mechanism, \( \lambda_0 \) represents the initial conformity coefficient; \( x_i \) represents the satisfied subsidy price after conformity learning; \( x_i \) represents the original satisfaction subsidy price; \( x_e \) represents the average expected price of group satisfaction subsidy; \( i \) represents a certain subsidy range; \( I \) means the set of all subsidy intervals.

Based on the dynamic function model of users’ economic satisfaction based on conformity psychology, the function relationship between \( \Delta f_i \) and \( \rho \) is calculated:

If \( \rho_0 \leq \rho \leq (\rho_0 + \rho_1)/2 \), \( \Delta f_i \) can be represented:

\[ \Delta f_i = \begin{cases} f_i, & x'_i - \rho \geq \Delta \rho \\ \frac{x'_i - \rho}{\Delta \rho} f_i, & 0 < x'_i - \rho < \Delta \rho \\ 0, & x'_i - \rho \leq 0 \end{cases} \]  

If \( (\rho_0 + \rho_1)/2 < \rho \leq \rho_1 \), \( \Delta f_i \) can be expressed:

\[ \Delta f_i = \begin{cases} f_i, & x'_i - \rho \leq 0 \\ \frac{x'_i - \rho}{\Delta \rho} f_i, & 0 < x'_i - \rho < \Delta \rho \\ 0, & x'_i - \rho \geq \Delta \rho \end{cases} \]  

\[ \Delta F(\rho) = \sum_{i \in I} \Delta f_i \]  

After the satisfaction evolution of all subsidy price ranges is completed, the probability function of economic satisfaction will change, and the distribution function obtained from the integration of the probability function of economic satisfaction after the change is the final user participation \( F'(\rho) \). Then, for a given subsidy price \( \rho \), the power \( P_a \) of DESS aggregation is:

\[ P_a = MP_{ESS} F'(\rho) \]  

4. Capacity optimization model of aggregator participating in peak load regulation based on users’ participation

Taking a single peak load as an example, the capacity optimization model of aggregator participating in peak regulation based on user participation is studied. The single peak type load curve is shown in figure 2. It can be seen that the peak-valley difference of load in this region is large and there is an urgent need for peak load regulation. According to the typical daily load curve and the set peak regulation target, the total power demand \( \Delta P_{\text{total}} \) and capacity demand \( E_{\text{total}} \) for peak load regulation in this region can be solved[9], and the functional relationship can be expressed as:

\[ \begin{cases} \Delta P_{\text{total}} = \delta P_{\text{us}} \\ \Delta E_{\text{total}} = \int_{T_1}^{T_2} (P_{L,t} - P_0) dt \end{cases} \]
where $P_{\text{max}}$ represents the maximum load power; $\delta$ denotes the set peak regulation target; $T_1$ and $T_2$ represent the start and stop times of peak adjustment; $P_{L,t}$ denotes load power; $P_0$ represents peak load target power.

![Graph 2](image2.png)
Figure 2. The single peak type load curve

![Graph 3](image3.png)
Figure 3. The influence of the initial conformity coefficient of participation function

| t (h) | P/MW | t (h) | P/MW | t (h) | P/MW | t (h) | P/MW |
|-------|------|-------|------|-------|------|-------|------|
| 0     | 22.50| 6     | 15.75| 12    | 35.18| 18    | 45.00|
| 1     | 18.90| 7     | 18.91| 13    | 36.92| 19    | 43.65|
| 2     | 17.18| 8     | 21.62| 14    | 40.05| 20    | 39.62|
| 3     | 15.32| 9     | 26.17| 15    | 41.44| 21    | 33.75|
| 4     | 13.95| 10    | 29.25| 16    | 44.12| 22    | 26.55|
| 5     | 14.85| 11    | 33.75| 17    | 44.10| 23    | 22.51|

Table 1. The load power

This paper comprehensively considers the benefits and costs of the aggregator, and takes the maximum annual net income as the objective function to establish the capacity optimization model of the aggregator participating in peak load regulation. The objective function is:
\[
\begin{align*}
\max f &= f_1 - f_2 - f_3 \\
f_1 &= L\rho_b E_a \\
f_2 &= L\rho_b E_a \\
f_3 &= \left(\lambda_p P_c + \lambda_r E_c\right) \frac{r(1+r)^{Y_{ESS}}}{(1+r)^{Y_{ESS}}-1}
\end{align*}
\] (14)

where \( f_1 \) represents the benefit of the aggregator participating in system peak load regulation; \( f_2 \) represents the cost of the aggregator to aggregate DESS; \( f_3 \) represents the cost of additional configuration of CESS by the aggregator; \( L \) is the number of annual peak shaving; \( \rho_b \) is the optimal subsidy price of the aggregator; \( c_r \) is the peak price; \( P_C \) and \( E_C \) represent the aggregator’s additional CESS power and capacity, respectively.

5. Case Study

The hierarchical ESS topology is shown in figure 1, and the load power of real time in this area is shown in table 1. The peak price period is 8:00-22:00, the price is 0.88 yuan/kWh. The rest of the time period is the valley price period, the price is 0.28 yuan/kWh, the discount rate \( r = 5\% \), the lower limit of subsidy \( \rho_0 = 0.1 \) yuan/kWh, the upper limit of subsidy \( \rho_1 = 1.1 \) yuan/kWh.

Taking \((\rho_0+\rho_1)/2\) as the critical point, the whole subsidy range is divided into the upper half and the lower half. Assume that the herd learning object is the entire interval. Based on the above model, change the initial lambda conformity coefficient \( \lambda_0 \), study the influence of the initial conformity coefficient of participation function. The figure 3 shows that engagement function are greatly influenced by initial conformity coefficient, with the increase of initial conformity coefficient, the critical values subsidies will be bigger, and saturated subsidies value will decrease, and tend to average subsidies value.

![Figure 4. The aggregator's annual net income](image)

![Figure 5. Load curves under different charging and discharging strategies](image)
Assumed $\lambda_0=0.2$, the peak adjustment target of the power system $\Delta 10\%$ is set. It is assumed that the annual peak adjustment times are 250 times, and the total number of users is 100 households, all of which are installed with 50kW/100kW•h DESS. According to calculation, the aggregator's annual net income under different subsidies is shown in figure 4.

As can be seen from figure 4, when the subsidy price $\rho_b$ is 0.7 RMB/kW•h, the aggregator has the maximum annual net income, reaching 376,200 RMB. At this time, the participation rate of DESS on the user side is 83.6%, and the aggregable capacity is 4.2MW/8.4MW•h.

When the peak regulation target is $\Delta 10\%$, the aggregator only needs to configure additional CESS of 0.4MW/0.8MW•h to achieve the purpose of grid peak load regulation. Load curves under different charging and discharging strategies for ESS are shown in figure 5.

As can be seen from figure 5, the capacity optimization method proposed can effectively play the role of peak regulation.

6. Conclusions
This paper proposes an ESS capacity optimization model for the aggregator based on users’ participation evaluation, which makes a preliminary exploration of the commercial value in the future under the background of electric power marketization. Through the example analysis and verification, the following conclusions are drawn: the problem of peak load regulation can be effectively solved by DESS aggregation and the corresponding charging and discharging strategy of ESS, and the valley value of load can be effectively improved and the peak-valley difference can be reduced.

However, in the course of the study, the consideration of the power market mechanism is relatively lacking, and the problem of the ESS market mechanism is idealized. For example, in the hierarchical architecture, only one aggregator is considered, and the game scenario of multiple aggregators under the power market mechanism is not considered.

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