The Capacity Optimization of the Energy Storage System used for Peak Load Shaving

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Abstract. With the development of society, the demand for power increases sharply, and the peak-valley difference of load curve will affect the power quality and the life of generator set. The energy storage system can be used for peak load shaving and smooth out the power of the grid because of the capacity of fast power supply. Because of the high energy storage cost, it restricts the wide use of energy storage system, so it is very important for optimizing the storage capacity allocation. This paper analyses the economic benefits of the battery energy storage system used for load shaving in the distribution network. Through genetic algorithm, and considering the investment costs and economic benefits of energy storage system, the optimal value of energy storage capacity allocation is obtained by maximizing annual income as the objective function which is based on time-sharing electricity price. Finally, a 17-node distribution network is tested with typical daily load curve to justify the effectiveness of this method, and the results show that this method can not only play the role of peak load shaving, but also obtain certain profits.

1. Introduction
As the load demand increases, the load fluctuation generated in the power grid becomes more and more obvious. The load fluctuation will affect the stability of the power grid, and even to the life of generator set, and in order to reduce the effects of load fluctuation, the grid company will invest a lot of manpower for peak load shaving and the main measures are: increasing generator installed capacity and the capacity for transmission lines. Both of these practices are not only large investment, but also inefficient. With the development of energy storage technology, it is an effective method to solve the load fluctuation by connecting the energy storage system to the distribution network. Because the energy storage system has the capacity of good power supply, it can transfer the user's power load and reduce the impact of peak load and valley load on the power grid. In addition, the energy storage system in taming scenery also plays an important role on renewable energy sources. In [1] establishes the user response decision model of benefit maximization as the goal for solar energy storage systems, to explore the capacity of energy storage device configuration, but it ignores the volatility of load demands and the intermittency of Photovoltaic (PV) power, so the conclusion remains to be further discussed. In [2] researches distributed energy storage optimization configuration method in distribution network with PV, with total capacity of energy storage configuration optimization as the target, the introduction of voltage fluctuation improves indicators to optimize the distribution of the energy storage capacity, and the simulation results show that adopting this method can reduce the energy storage capacity by 85% with strong practicability.

At present, the large-scale energy storage system has entered into the business model abroad. In 2016, Japan's new large-scale energy storage projects for almost all applications in the field of electric power distribution was established in 2020, and the Japanese manufacturers of energy storage battery
production occupies 50% market share of the global development goals. In order to achieve this goal, Japan fully implements the battery storage subsidy and incentive plan in the practical application of power generation, transmission, distribution and use of various links. But the domestic energy storage system application is still in the experimental stage and small-scale operations. Wuxi Singapore industrial park intelligent distribution network energy storage power station, the total power energy storage power station is 20 MW, the total capacity is 160 MWH, and it is currently the largest domestic commercial energy storage power station.

According to the technical requirements of energy storage system access distribution network: the energy storage system can be connected in the form of power or load. At present, in most parts of the country, the mode of time-sharing electricity price is adopted, and the time-sharing price mechanism is the charging method of electricity price charged in time-sharing section: when the load demand is high, the electricity price is relatively high. When the demand for load is low, the electricity price is low, which creates economic significance for cutting peak loads. Based on this charging mechanism, the energy storage system can charge at valley price and discharge when the load demand is large. The energy storage system not only realize the smooth output of the power grid, but also realize the arbitrage. However, one of the key reasons for restricting the large range of energy storage batteries is the cost is too high, so experts and scholars are devoted to the optimization model of energy storage capacity. In [3] optimizes the different ways of storage capacity under the peak valley price in distribution network, thinking that the economic benefits of compressed air energy storage (CAES) is higher, but it ignores that CAES has relatively high topographic requirements, which does not take into account the actual engineering application scenario. In [4] the capacity optimization configuration is carried out in the system with the PV and wind power, and the double-level optimization model was established, the outer based on genetic algorithm optimization, inner optimal power flow optimization based on SQP. Finally, it draws energy storage capacity of the optimal value by an example. In [5] is based on economic dispatch to analyse the optimal allocation of energy storage, and to use the improved genetic algorithm to solve the optimal value of energy storage, which has certain improvement significance.

In summary, the commonly used energy storage capacity allocation method is mainly based on optimization algorithm [6]. The objective function is usually the minimum capacity of energy storage system, or the minimum system cost. Based on time-sharing price model, using MATLAB genetic algorithm (GA) toolbox, with annual revenue maximization as the objective function, to optimize the energy storage system capacity, and to the distribution network with 17 nodes object, using the typical daily load curve for example analysis. The results show that this method can optimize the capacity of energy storage system and has good economic value.

2. Analysis of the strategy of peak load shaving in energy storage system

Battery energy storage system has the advantages of fast response and high power supply, so it has a wide application in peak cutting [7]. The battery energy storage can participate in the peak shaving, and according to the daily load curve, different charging and discharging strategies are developed, such as "one charge and one discharge" in a single day, and "one charge and two discharges". There are two kinds of control methods: constant power control and power difference control in the figure 1.

![Figure 1. Load curve.](image1)

![Figure 2. Time-sharing tariff.](image2)
The constant power charging and discharging control strategy is based on the energy storage battery charging and discharging energy, so it is necessary to ensure that the charge and discharge time is equal every day, and the control method is simple. Typical daily load curve as shown in a given area, adopt the strategy of "one charge and one discharge". The red curve is expected to peak sharpening effect, the actual load is shown in black and the charge and discharge time are 9 hours respectively. This method is relatively simple to control and reduce the peak value of load to a certain extent. But this kind of control strategy depends on the load curve forecasting, and as predicted by the load curve does not agree with the real load, this control method can not meet peak shaving goal, this is a kind of based on load curve is lesser known or load change control strategy. Because the constant power control strategy is simple and practical, it is widely used in practical engineering. The power difference control mode can realize the smooth output power of the power grid. The blue curve shows the optimized curve of the power difference strategy, and the peak filling effect is better than the constant power control strategy. The power difference control strategy can effectively reduce the load pressure of the power grid and the huge investment. The power difference control method can respond to the real-time load condition, and the output power of the energy storage system can be configured according to the power difference at different moments. The advantage of dynamic adjustment is that the control precision is high, and the peak shaving is better. This paper is based on the power difference control method.

3. Economic analysis

3.1 Economic benefits in distribution network

In the distribution network, the energy storage system can not only improve the stability of the system, but also generate certain economic benefits. Under the mechanism of time-sharing electricity price, energy storage batteries can be arbitrated through "low storage and high release". Factories such as commercial electricity peak valley price difference is close to 0.8 yuan/kWh, the residential electricity peak valley price difference of about 0.3 yuan/kWh. In the larger distribution network, with larger economic sense, also promote the energy storage system for peak cut a favorable factor. In addition, when the load fluctuation is large, the energy storage system can reduce the number of cutting, prolong the service life of the unit and reduce the cost of equipment input. At the same time, it can reduce the loss of the line and generate certain economic benefits [8].

3.1.1 Economic benefit of time-sharing price

At present, the electricity market generally adopts the charging mode of time-sharing electricity price. In the case of a certain area, at the peak of the load, the electric charge was 0.6583 yuan/kWh, when the load was low, the electric charge was 0.3583 yuan/kWh. In the figure 2, the price difference of peak valley was about 0.3 yuan/kWh, and the peak valley price difference of industrial electricity consumption reached 0.8 yuan/kWh. With distributed energy storage, it can realize the arbitrage in time-sharing pricing mode. Assuming that the battery adopts the constant power charging and discharging mode and does not consider the peak valley price difference of industrial electricity consumption. The price difference of the peak valley is $q$, and $t$ stands for discharging time, $P_t$ representing the real-time output power of the energy storage system. Then, the annual economic benefit in the distribution network is expressed as: $F_1=0.1 \sum_{i=1}^{365} \sum_{r=8}^{22} qP_t$.

3.1.2 Government subsidies

In 2016, the ministry of finance and the national development and reform commission promulgated the interim measures on the administration of the central financial incentive fund management for the comprehensive pilot work on power demand side management. The method is pilot in some areas, and it gives certain financial subsidy to the related enterprises. To improve the energy efficiency of power equipment, the reform project of saving power load permanently will be divided into three categories: 300 yuan/kW, 400 yuan/kW, 500 yuan/kW. Suppose the power capacity subsidy of the government is $b$, so the annual subsidy is: $F_2=1000bP_{add}$. 


3.2 cost analysis of distributed energy storage devices
The investment cost of distributed energy storage device mainly includes the cost of equipment purchase in the early stage and the maintenance cost of the later equipment. The cost of equipment purchase and energy storage capacity and power are all related. Maintenance costs are mainly related to power supply [9].

3.2.1 initial investment cost analysis
The initial investment cost of energy storage device mainly includes equipment cost and energy management system cost. The cost of equipment is related to the capacity of energy storage system, and the cost of energy management system is related to the power of energy storage system. The cost of the energy storage capacity is 1 million yuan /MWh, the total capacity of the battery energy storage system (BESS) is E_{add}, the cost of energy storage power is 20,000 yuan/MW. The total investment cost can be expressed as: \( F3 = (f1E_{add} + f2P_{add}) / m \), so the average annual investment cost can be expressed as: \( F3 = (f1E_{add} + f2P_{add}) / m \), m stands for the BESS whole life.

3.2.2 analysis of investment cost maintenance
After the energy storage device is put into use, the maintenance of the system and the maintenance of loss is required. The annual maintenance investment fee can be expressed as: \( F4 = rP_{add} \), where \( r \) represents the annual maintenance cost of unit power. According to the actual demand of peak shaving, the whole vanadium liquid battery energy storage system is selected, and the whole vanadium flow battery is compared to the lead-acid battery, which has higher energy density and higher discharge depth. Compared with lithium battery, it has less investment cost. Full - vanadium - flow battery charging and discharging depth, without affecting battery life. Therefore, it is the first choice and the technology is more mature. In 2016, Dalian Rongke company obtained the 200MW/800MWH full vanadium flow battery energy storage peak power station project, which is currently being implemented in an orderly way.

4. Optimized allocation model of energy storage capacity
Because of the high cost of energy storage system, it is difficult to get a large scale promotion. At present, it is popular to study the optimal allocation of energy storage capacity. The result of optimal configuration is to meet the demand of users and to achieve the optimal economic performance. Through the MATLAB GA toolbox, the objective function and constraints are set up to calculate the optimal allocation of energy storage capacity.

4.1 determine the objective function
According to the above analysis, from the perspective of investors, under the condition of considering power market, the objective function is to maximize annual income, which is expressed as:
\[
T = \max \left( F1 + F2 - F3 - F4 \right) \tag{1}
\]

4.2 establish constraints
Node power constraint: when the power system is in stable operation, it must meet the balance of power supply. In particular, at node i, the active power needs to be balanced, ignoring the line loss, and the power relationship of the energy storage system is as follows:
\[
P_{r} + P_{G} = P_{L} \tag{2}
\]
The \( P_{L} \) represents the load power of the distribution network, and \( P_{G} \) represents the load power of the power grid.
System operation constraint: in order to prevent the occurrence of the voltage limit of distribution network, the system needs to meet certain constraint conditions. In particular, at node i, the voltage and power of the node need to be within a range and cannot be limited [10].
\[
U_{i_{\text{min}}} \leq U_{i} \leq U_{i_{\text{max}}} \tag{3}
\]
\[
P_{i_{\text{min}}} \leq P_{i} \leq P_{i_{\text{max}}} \tag{4}
\]
The constraint condition of energy storage battery: in order to ensure the safe and stable operation of energy storage battery, it is necessary to meet the constraint of power and the constraint condition of battery charge state.
The relationship between energy storage capacity and power: the capacity of the energy storage system is the power output at the unit time, and the relationship is as follows:

\[ P_{\text{battery}} \text{min} \leq P_{\text{battery}} \leq P_{\text{battery}} \text{max} \]  

(5)

\[ \text{SOC} \text{min} \leq \text{SOC} \leq \text{SOC} \text{max} \]  

(6)

The formula, \( t_1 \) and \( t_2 \) is the discharging start-stop time of energy storage battery.

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4.3 GA is used to solve the problem

GA, also known as evolutionary Algorithm, is inspired by Darwin’s theory of evolution and a heuristic search Algorithm proposed by the evolution of biology [11]. MATLAB comes with the genetic algorithm toolbox, the genetic algorithm is a method to search the global optimal solution, mainly used to solve the function optimization problem. The genetic algorithm is used to determine whether the first objective function is correct and the second constraint is reasonable.

The procedure for solving genetic algorithm is as follows:

![Figure 3. The GA flow chart.](image)

5. Case analysis

5.1 Calculation example overview

**Distributed power access network technology regulation**: distributed power supply access voltage level is appropriate: 200kW and the following distributed power supply connected to 380V voltage rating grid; More than 200kW distributed power supply to 10kV and above voltage rating grid. This paper selects the distribution network of 17 nodes, as shown in the figure 4. Node 1 is connected to the high voltage grid. In the distribution network, assuming the load demand is known, the typical daily load is used as the average load. The maximum power value in this example is 32.25MW and the minimum power value is 14.01MW [12]. Suppose that two sets of energy storage devices are installed in this distribution network, and two energy storage devices are installed on node 5 and node 14 respectively. The energy storage system is connected to the distribution network by the converter, which realizes the charge and discharge control and ignores the addressing problem of the energy storage system. According to the time price table above, the electricity price is the peak price at 8:00-22:00, and the distribution network load is supplied by the energy storage battery and the power grid, and the energy storage system is connected to the power supply. The other time load is relatively small, can be directly supplied by the power grid [13], [14]. During this period, the energy storage battery is connected to the power grid as a load, and the system is charged to ensure that when the next peak price arrives, it can supply the load in time.

5.2 Calculation results

The optimal energy storage power configuration is 4MW through genetic algorithm, and the annual income is 0.630003 million yuan. Because the solution model adopts the ideal situation, the actual profits will have some error.
Further analysis of the relationship between benefits and power cost and peak valley electricity price is shown in the figure 5. As can be seen from the figure 5, when the peak valley price difference is 0.5 yuan/kWh, the annual income can reach 1.03 million; When the power cost goes down to 2.14 million yuan/MW, the annual revenue will reach about 1 million. The application of energy storage battery has a very broad prospect in the future.

| Table 1. Parameter Settings. |
|-----------------------------|
| parameter | Value |
| r | 23 |
| m | 20 |
| q | 0.3 |
| b | 0.04 |
| f1 | 105 |
| f2 | 481 |

**Figure 4.** 17 node distribution network.  
**Figure 5.** the relationship between benefits and power cost and peak valley electricity price.

6. **Conclusions**
1. The energy storage battery has good power supply capacity, and it has a good effect on cutting peak load. With the decrease of energy storage power cost, the application of energy storage battery for peak load shaving will be widely promoted.
2. When the peak valley electricity price difference is relatively high, the profit situation is obvious, so it will be more obvious to install the energy storage system in the industrial park.
3. Based on current storage costs, direct arbitrage condition is not very obvious, but the indirect benefits cannot be estimated. For the power grid, it has important application value, so the study of the energy storage technology will be a topic for a long time.

With the promotion of the energy Internet, the energy storage battery will be further developed, and the future energy storage technology will be widely used in the power system. The development of smart grid requires the continuous improvement of emerging technologies.

7. **Acknowledgements**
I really appreciate the help from my tutor and classmates. With their help, I finished the paper.

8. **References**
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