Review of Optimal Allocation Methods of Energy Storage in Different Applications of Power System

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Abstract. With widely application of energy storage technology in power system, the function and configuration method of energy storage system (ESS) in different scenarios have become the focus. In the grid side, energy storage can participate in safety accident response, power grid frequency control, peak shaving, power grid upgrading delay and easing transmission line congestion, etc. In the power supply side it is mainly used to improve the power supply flexibility and controllability; In the user side it is mainly used to improve power quality, arbitrage through peak valley, as well as providing uninterrupted power supply to ensure reliability. Due to different application conditions and purpose under different scenarios, energy storage configuration requirements are also vary. So it leads to various configuration method and lack of a unified evaluation index. In this paper, the existing optimization configuration method their respective advantages and disadvantages are analyzed, and then, the ideas, principles and basic evaluation index in common scenario are summarized. It provides reference basis for energy storage optimization in power system.

Keywords: energy storage allocation, grid side, power supply side, user side.

1. Introduction

At present, the research review on the application of energy storage in power system mainly focuses on the development status, the characteristics comparison, the application scenarios, the key technical directions and the control technology of energy storage [1-6]. Review of energy storage planning and configuration is relatively rare, and it is impossible to fully grasp the current status of planning and configuration technology of energy storage in different scenarios of power grid. The planning and configuration must meet the requirements of system operation and reduce operating costs, therefore, balancing technical performance and economic indicators is a key issue. According to the number of optimization targets, the classification methods of energy storage planning can be divided into single target optimization and multi-objective optimization; According to the optimization object, it can be divided into technical index optimization method, economic index optimization method and both methods. According to the applicable scenarios, it can be divided into three major scenarios: the power grid side, the power source side, and the user side. Based on the different application scenarios of energy storage in power system, the optimal configuration method of energy storage in different
application scenarios from the technical and economic perspectives is analyzed in this paper, and the widely used optimization models and principles are summarized and proposed.

2. Planning and allocation methods of energy storage in the grid side

Energy storage in the grid side refers to that directly connected to the utility grid. The main functions of them are undertaking accident safety response, assisting power grid peaking and frequency modulation, cutting peaks and valleys, delaying grid upgrades, and reducing transmission line congestion.

2.1. Energy storage configuration for grid peak shaving

The study of energy storage for peak shaving mainly involves peak clipping and valley filling of the grid load, and considering the anti-peaking characteristics of wind power, using energy storage to cut peaks and fill valleys to improve wind power acceptance. Most of the research is based on economics, considering the peak and valley electricity prices, and the electricity efficiency and other indirect benefits of wind power acceptance. Literature [7] proposes a capacity allocation method considering the relaxation of peaking bottleneck after wind power access. This method utilizes energy storage to improve wind power acceptance during the low load period, and takes the maximum benefit of the ESS in the operation period as the optimization goal, and constrains the energy storage investment cost and economic benefit, and considers the improvement of the electricity revenue received by wind power, the operating income of time-of-use electricity price, and the environmental benefits such as emission reduction and recycling. Literature [8] proposes a method of energy storage configuration for peak shaving and valley filling. This method takes the sum of the power, capacity and environmental benefit and deducting the cost of the energy storage as the objective function, and solves the energy storage capacity and cost when the investment income is obtained. Literature [9] proposes a comprehensive benefit evaluation method for wind-storage combined system considering wind power output uncertainty and power grid peaking capacity limitation. This method takes the maximum probability of comprehensive benefit of the combined operation of wind and energy storage in the energy storage life cycle as the optimization goal, taking into account the revenue of time-of-use electricity price, wind and environmental benefits, and the cost of energy storage. The above models are all single objective functions of economic benefits.

Literature [10] and [11] respectively proposed a two-layer optimization model to determine the optimal location and capacity of ESS. Literature [10] takes the lowest expected operation and the investment cost of energy storage as the upper target, and the lowest operating cost of the typical day as the lower target. The upper and lower layers of the model consider different constraints, and the bi-level programming model is transformed into a linear mixed integer programming model based on dual theory. Literature [11] proposes a bi-level programming model, The outer layer of the model is based on the minimum net present value of the distribution network in the life cycle of the project, to select the capacity of the ESS. The inner layer realizes the optimal power flow and capacity adjustment based on the battery life. Among them, the optimal power flow is optimized by the load peak-to-valley difference and the minimum network loss.

In summary, the research on peak shaving of energy storage auxiliary power grids mainly focuses on economics [7-21], and the emphasis is slightly different. The main objective function is that the total operational efficiency of the system with ESS is the largest [7-13], the total system operation and energy storage investment cost is the smallest [14-18], and the net energy storage income is the largest [19-21]. The constraints mainly include the normal operation constraints of the power grid and the investment constraints of energy storage. Such methods have reference significance in solving the peaking of power grids and reducing the abandonment of new energy.
2.2. Energy storage configuration for grid frequency modulation

At present, the capacity allocation of energy storage for frequency modulation is still in the exploratory stage, mainly based on the measured data to establish a frequency response model, combined with economic benefit assessment, to obtain the energy storage capacity results that make the system performance or economical optimal [22-25].

From the frequency modulation performance, literature [26] uses a strategy of superimposing additional charging and discharging power in real time on the depth of energy storage action to minimize the energy storage capacity configuration, but this method increases the operating cost of energy storage. Literature [27] uses energy storage as an add-on to the static var compensator. Literature [28] proposed a battery ESS control strategy to stabilize the frequency fluctuation of wind farms. The simulation results of this strategy show that the battery energy storage and wind power installation in the same area have the best frequency modulation effect and the minimum required capacity configuration.

From the system economy, the literature [29] proposed the optimal allocation strategy of ESS capacity and operation mode for frequency modulation in water, fire and wind power systems. The strategy uses the net present value (NPV) as a performance indicator to maximize operational efficiency, with the maximum annual economic benefit as the optimization goal, and the objective function is as shown in equation (1):

$$\max \ NPV_{\text{profit}} = \max \sum_{t=1}^{T} \frac{1}{(1+r)^t} (P_{\text{reserve}} + P_{\text{selling}} - C_{\text{BESS}} - C_{\text{recharge}})$$

(1)

Among them, $P_{\text{reserve}}$ is the available value of the frequency control reserve, $P_{\text{selling}}$ is the compensation for selling excess energy in the spot market, $C_{\text{BESS}}$ is the cost of energy storage equipment, and $C_{\text{recharge}}$ is the cost of energy storage charging. Literature [30] proposes a method for economically optimizing the scale of ESS, with the goal of maximizing the total net income of wind farms during the life cycle of ESSs and minimizing the energy storage capacity required to participate in frequency modulation.

In summary, the optimal configuration of energy storage for frequency modulation is aimed at satisfying the requirements of frequency, on the one hand, the goal of maximizing net present value or minimizing energy storage cost. The better the FM performance, the higher the stored energy and the higher the cost. Therefore, how to find a balance between the FM performance and the economy is the key to this problem. There is no mature method at present.

2.3. Energy storage configuration for improving distribution network operation and economy

ESS can also be used to reduce network losses, improve stability, and regulate voltage. Literature [31,32] uses the loss reduction as an important reference indicator for energy storage planning. Literature [32] proposes an energy storage capacity optimization model with the goal of minimizing the network loss and a network loss sensitivity analysis method for energy storage optimization and location selection under three-phase unbalanced conditions. Literature [33] proposes a method for energy storage location and capacity optimization based on transient stability risk. The method can measure the function and effect of ESS according to the transient stability risk indicator. Literature [34] proposes a multi-objective optimization model for energy storage to adjust the peak voltage of distribution network. The multi-objective problem is transformed into a single-objective and solved by sequential quadratic programming algorithm. The first objective function is that the annual cost of the ESS is the smallest, as in equation (2):

$$K_{\text{tot}} = K_{\text{depr}} + K_{\text{fix}} + K_E$$

(2)
Among them, $K_{depr}$ is the depreciation cost of the battery, battery peripherals and inverter; $K_{fix}$ is the fixed capital cost and maintenance cost; $K_e$ is the average cost of energy storage per unit time.

The second objective function is to minimize the maximum peak voltage fluctuation, as shown:

$$
\Delta U_{\text{peak}} = \sqrt{\frac{1}{n_d \sum_{d=1}^{n_d} \sum_{k=1,2,3} |U_{p,h,k} - U_{\text{nom}}|^2}}
$$

(3)

Among them, $\Delta U_{\text{peak}}$ is the root mean square value of all daily peak deviations during the evaluation period; $U_{p,h,k}$ is the grid peak voltage; $U_{\text{nom}}$ is the grid rated voltage; $n_d$ is the number of days in the evaluation period, and $\kappa_j$ is the time step in $d$ days.

The third objective function is that the RMS of the peak power is the smallest, as in equation (4):

$$
S_{\text{rms}}^{\text{peak}} = \sqrt{\frac{1}{n_d \sum_{d=1}^{n_d} \sum_{k=1,2,3} \left| S_{\text{tot}}^{\text{peak}} \right|^2}}
$$

(4)

Among them, $S_{\text{tot}}^{\text{peak}}$ is the total composite power consumption of quadrant $p$.

The ESS will bring huge economic benefits when it is connected to the distribution network. The literature [35, 36] establishes an economic evaluation model for energy storage in distribution networks based on the benefits of electricity price arbitrage, reduction of transmission costs, and delays in equipment investment.

3. Planning and allocation methods of energy storage in the power supply side

Energy storage in the power supply side refers to the ESS installed in the power plant of the conventional power plant, wind farm, pv power station, etc, mainly responsible for peak and frequency modulation. In such applications, energy storage and conventional power or new energy are externally combined, and the location is basically determined, with a focus on the configuration of capacity. Because the micro-grid can be equivalent to a power point, the planning of the micro-source containing energy storage is also classified as the application in the power supply side.

3.1. Energy storage configuration in the conventional power supply side

The application of energy storage in the conventional power supply side is mainly to improve the adjustment flexibility of the conventional power supply. Literature [37] proposed a capacity allocation method for energy storage auxiliary thermal power units participating in system frequency modulation. Literature [38] allocates the optimal capacity and power of the thermal energy storage based on the forced outage rate of the thermal power unit and the peak-valley characteristics of the grid system load curve.

In summary, the application of energy storage in the conventional power supply side is mainly to improve the flexibility of conventional power supply regulation, for example, auxiliary thermal power unit frequency modulation. In terms of site selection, it is usually designed in conjunction with the energy system, and most of the capacity configuration considers load characteristics and functionality.

3.2. Energy storage configuration in the new energy side

The application of ESS with new energy is more focused on the optimization of new energy output and the impact on power quality after energy storage access, such as smoothing fluctuations, tracking planned output, and improving the active support capacity of new energy power stations.

Mitigation of new energy power fluctuations includes the suppression of large new energy power plants and distributed new energy sources, and its capacity allocation is closely related to the output power characteristics of new energy sources. The optimal configuration method for smoothing fluctuations is usually based on the measured historical data to analyze and extract the characteristics of
new energy power fluctuations. In the selection of energy storage types, a large number of studies tend to use hybrid ESSs with battery storage and super-capacitors. Super-capacitors are used to stabilize short-term scale power fluctuation, while battery storage is used to stabilize long-term power fluctuations. Literature proposes a power and capacity optimization scheme for ESS based on the standard deviation of output power fluctuations of wind turbines and energy storage devices. Literature use the discrete Fourier transform to perform spectrum analysis on the renewable energy output, and based on the spectral analysis results and the relevant constraints of ESS, determines the minimum capacity of the ESS required to smooth power fluctuations.

The energy storage can also track the planned output of new energy to reduce the power forecasting error, thereby reducing the abandoned electric quantity. Literature proposes a capacity allocation method for ESS that takes into account the differences in the wind-restricted period, the distribution characteristics of the wind-restricted power, and the power efficiency, environmental benefits, investment costs and maintenance costs of ESS, and dividing the scene of multi-scenario regulation of ESS. Literature proposed an optimal allocation method for energy storage capacity considering the uncertainty of wind power prediction error probability distribution. The method takes the sum of the energy storage configuration capacity of each node as the optimization goal, and analyzes the influence of wind power prediction error accuracy, chance constraint confidence, and wind power volatility on the energy storage capacity. Literature proposed an energy storage optimization model with the maximum benefit of wind farms as the optimization goal. The model adds confidence in compensating wind power prediction error as a chance constraint, and considers the correction of the wind power forecast output curve.

Regarding the ESS to improve the active support of new energy power stations, the current literature has done a lot of research on control methods such as virtual synchronous control and equivalent inertia control, but the capacity allocation of energy storage has not yet been reported. The application of energy storage with new energy is mainly to stabilize fluctuations, optimize output, improve power quality and reduce output error. The economic goal of optimal allocation of energy storage capacity is mainly comprehensive benefits including power efficiency, environmental benefits, energy storage costs.

3.3. Energy storage configuration in the micro-grid

The micro-grid has two typical modes of grid connected and islanding. Under normal conditions, the micro-grid runs with the grid. When the grid fault or power quality event is detected, the micro-grid will be disconnected from the grid in time. When the micro-grid is connected to the grid, the ESS plays a role in maintaining the stable operation of the micro-grid. When the off-grid is running, the ESS acts as the main power source that providing voltage and frequency support. Certain energy storage is needed in the system to ensure smooth switching between the two modes and ensure the stability of the system. Literature proposed a wind power micro-grid power supply configuration method, which uses the energy storage device as the main micro-source, and uses the neighborhood mean filtering method to distribute power between the battery and the super capacitor. Literature proposed a capacity optimization model for micro-grid battery energy storage. The model takes the minimum annual system cost as the optimization goal, the battery ESS charging and discharging power as constraints, and considers the operating characteristics of the battery energy storage to affect its life. Literature proposed an optimal configuration model for thermoelectric energy storage based on economic dispatch. Considering the random factors in the micro-grid, the artificial bee colony algorithm is used to optimize the model in various scenarios. By comparing the comprehensive cost of the micro-grid under different energy storage capacities, the optimal energy storage scheme is obtained.

In the micro-grid, especially in the micro-grid with new energy generation, the ESS should not only use the ESS to improve the power quality of the micro-grid, but also smooth the fluctuation of the output of the new energy source, and also necessary to consider the stability of the micro-grid grid-connected
operation and off-grid operation system, reduce the cost of the ESS and improve the economic benefits on the basis of satisfying the stable operation.

4. Planning and allocation methods of energy storage in the user side
User-side energy storage helps to achieve demand side management, ensure power supply reliability, improve power quality, and arbitrage for users. The income forms are more, including reducing user electricity bills and reducing user power outage losses. Most studies of optimal configuration of energy storage on the user side focus on the evaluation of the value in user side\(^\text{[52-55]}\). Literature [52] proposes an energy storage optimization model with the minimum power outage cost as the objective function based on the application of ESS in emergency standby, and key point is to prioritize powering small commercial and commercial loads without backup power during power outages. The objective function is as follow:

\[
\min \sum_{n=1}^{N} C_n \cdot CDF_t (t_{out} - X_n, \sum_{n=1}^{N} W_n, S_n) \\
X_n \in \{0, 1\} \forall n \\
\sum_{n=1}^{N} |X_n P_n| < P_{max}
\]  

(5)

Among them, \(n\) is the load index, \(C_n\) is the number of users of load \(n\), \(CDF_n\) is the user damage function of load \(n\), \(t_{out}\) is the duration of system outage, \(X_n\) is the indicator variable of load \(n\), \(X = 1\) is service and \(X = 0\) is offline, \(S_n\) is the average kVA demand for load \(n\) during a power outage. Each item in the summation of the objective functions is the expected cost of a power outage at a particular load point. Literature [53] considers the economic value of battery energy storage on the user side in many aspects, and proposes that the maximum annual energy harvesting income based on the time-of-use electricity price of each time period is the objective function. The function is as follow:

\[
\max E_{year} = E_1 + E_2 + E_3 + E_4 + E_5 - C_1 - C_2
\]

(6)

Among them, \(E_1\) is the benefit of the BESS system to reduce the construction capacity of the user's substation, \(E_2\) is the reduced basic electricity cost for the user, \(E_3\) is the reduced cost of purchasing electricity, \(E_4\) is the reduced cost of the distribution transformer, and \(E_5\) is the benefit of reducing the cost of power outages, \(C_1\) is the energy storage investment cost, \(C_2\) is the annual operation and maintenance cost.

5. Conclusion
In summary, the energy storage configuration in the grid side is mainly based on comprehensive consideration of technical indicators and economic benefits, two-layer or even three-layer planning model for energy storage site selection and capacity optimization is establish. The energy storage in the power supply side is mainly combined with a specific power point or micro-grid, considering the power performance and fluctuation indicators, the power capacity of the ESS is optimally configured in the corresponding scenario, which can improve the flexibility of conventional power supply frequency regulation, stabilize the power fluctuation of new energy, and maintain the stable operation of the micro-grid. The energy storage configuration in the user side mainly considers arbitrage for users while improving power quality, realizes user demand side management and helps new energy consumption and utilization, mostly based on economic indicators such as lowest user cost or maximum revenue.

With the advancement of energy storage technology and the decline of cost, the application of energy storage in power systems is more and more extensive. How to play a multi-faceted comprehensive role and benefit is the key point to consider in energy storage planning. The difficulty in
energy storage configuration for frequency modulation is how to coordinate primary frequency modulation and secondary frequency modulation, and how to measure the economic benefits of energy storage participating in frequency modulation.

References


[37] Ding Dong, Yang Shuili, Li Jianlin, et al. BESS Capacity Configuration of Auxiliary Thermal


