Research on Optimal Configuration of Hybrid Energy Storage Capacity Based on Life Cycle Cost

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Abstract. The defect of the fluctuation of the photovoltaic power generation system output power leads to the serious phenomenon of photovoltaic curtailment, and the energy storage technology can effectively solve the problem of photovoltaic curtailment. Reasonable allocation of the capacity of the hybrid energy storage system (HESS) is an important guarantee for the reliable operation of the HESS. To solve the above problems, the HESS is composed of lithium battery and super capacitor (SC) . Taking the life cycle cost (LCC) of energy storage components into account, state of change (SOC) and power constraint as constraint conditions, the energy storage economic evaluation model is established. The example analysis verifies that the proposed method can effectively improve the overall operation economy of the HESS, and has certain reference value for engineering practice.

Keywords: HESS; Life cycle cost; Photovoltaic power

1 Introduction

Due to the influence of external environment, the random fluctuation of the output power of photovoltaic power generation system will have an impact on large-scale grid-connection of photovoltaic power stations[1-3].The HESS composed of power-type energy storage components and energy-type energy storage components can effectively improve the output power fluctuation of renewable energy, but due to the limitation of technological development, the cost of energy storage components has always been high[4]. How to effectively use energy storage system to smooth power fluctuations and optimize the operation economy of energy storage system has become the main development direction at present.

In response to this topic, domestic and foreign scholars have also done relevant research, mainly around the decomposition of photovoltaic power and energy storage system capacity configuration two aspects. Some progress has been made in the research on decomposition of photovoltaic power, but the research on energy storage

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capacity optimal allocation is still in the preliminary stage. literature [5] proposes a comprehensive control strategy for wide-area energy storage system, and finds the optimal energy storage control strategy through comparative analysis of the results of energy storage capacity allocation under different control strategies. literature [6] proposed an energy storage capacity estimation method based on the normal distribution of short-time power prediction errors; literature [7] proposed a capacity allocation method of wind and solar storage system based on the analysis of spectrum characteristics;literature [8] proposed a smoothness grade index to quantitatively evaluate the smoothed PV power smoothness. The method combining empirical mode decomposition and neural network is used to realize the rational allocation of energy storage capacity. Monte carlo method is used to simulate and analyze the operating state of the system and modify the initial configuration of energy storage. most of the existing studies on capacity allocation take the climb rate of grid-connected power as the optimization objective, and few consider the operation economy of the energy storage system during the whole life cycle.

Based on the power of the HESS, fully considers the complementary characteristics of different energy storage, makes equivalent calculation based on the LCC of energy storage components, and establishes the economic evaluation model of the capacity allocation of the HESS. The improved particle swarm optimization algorithm is used to solve the average annual cost, and the load configuration scheme of the energy storage system with the lowest average annual cost in the whole life cycle of the HESS is obtained.

2 Establishment of Economic Evaluation Model of Energy Storage System Based on the Life Cycle

The LCC refers to the sum of all costs related to the product during its effective use . The LCC C of the HESS mainly focuses on the investment cost C_B of lithium batteries and SC, and the maintenance cost C_M during the operation of the energy storage system. And the replacement cost C_R after the end of the life of the energy storage device and the waste disposal cost C_D. The annual average life cycle cost of the HESS with a service life of T is calculated as follows:

$$\begin{cases} C_{\mathrm{B}} = \mathrm{B}_{\mathrm{li,p}} \cdot P_{\mathrm{li}} + \mathrm{B}_{\mathrm{sc,p}} \cdot P_{\mathrm{sc}} + \mathrm{B}_{\mathrm{li,c}} \cdot C_{\mathrm{li}} + \mathrm{B}_{\mathrm{sc,c}} \cdot C_{\mathrm{sc}} \\ C_{\mathrm{M}} = \mathrm{T} \cdot (\mathrm{M}_{\mathrm{li}} \cdot C_{\mathrm{li}} + \mathrm{M}_{\mathrm{sc}} \cdot C_{\mathrm{sc}}) \\ C_{\mathrm{R}} = \mathrm{R}_{\mathrm{li}} (\mathrm{B}_{\mathrm{li,p}} \cdot P_{\mathrm{li}} + \mathrm{B}_{\mathrm{li,c}} \cdot C_{\mathrm{li}}) + \mathrm{R}_{\mathrm{sc}} (\mathrm{B}_{\mathrm{sc,p}} \cdot P_{\mathrm{sc}} + \mathrm{B}_{\mathrm{sc,c}} \cdot C_{\mathrm{sc}}) \\ C_{\mathrm{D}} = \mathrm{D}_{\mathrm{li,p}} \cdot P_{\mathrm{li}} + \mathrm{D}_{\mathrm{sc,p}} \cdot P_{\mathrm{sc}} + \mathrm{D}_{\mathrm{li,c}} \cdot C_{\mathrm{li}} + \mathrm{D}_{\mathrm{sc,c}} \cdot C_{\mathrm{sc}} \\ C = \min(C_{\mathrm{B}} + C_{\mathrm{M}} + C_{\mathrm{R}} + C_{\mathrm{D}}) / \mathrm{T} \end{cases} \quad (1)$$

Where P_{li} and P_{sc} are power of battery and SC; where C_{li} and C_{sc} are rated capacities of battery and SC; $B_{li,p}$, $B_{s,p}$ are the unit power prices of battery and SC; $B_{li,c}$, $B_{sc,c}$ are capacity unit prices of battery and SC. M_{li} and M_{sc} are the maintenance unit prices of battery and SC. R_{li} and R_{sc} are the number of replacement times of battery and SC during the operating cycle; $D_{li,p}$, $D_{sc,p}$ are the unit prices of power disposal of battery and SC; $D_{li,c}$, $D_{sc,c}$ are unit prices for disposal of battery and SC capacity.

2.1 Energy conservation constraint

The original PV output should be equal to the sum of grid-connected target power and energy storage power, and the corresponding power distribution formula is:

$$P_{\mathrm{m}}\left(t\right)+P_{\mathrm{out}}\left(t\right)=P_{\mathrm{w}}\left(t\right) \tag{2}$$

$$P_{\mathrm{li}}\left(t\right)+P_{\mathrm{sc}}\left(t\right)=P_{\mathrm{m}}\left(t\right) \tag{3}$$

Where $P_{\mathrm{w}}(t)$ is the PV original output; $P_{\mathrm{out}}(t)$ is the grid-connected target power.

2.2 State of charge constraints for energy storage elements

Due to the overcharging and discharging phenomena of energy storage components, their service life can be reduced. Therefore, it is necessary to limit the SOC of lithium batteries and SC to a reasonable applicable range. The calculation formula for the state of charge of energy storage is as follows:

$$SOC(t)=SOC(t-1)+\frac{\omega_c P_c(t)\eta_c-\dfrac{\omega_d P_d(t)}{\eta_d}}{E} \tag{4}$$

$$SOC_{\min}(t)\le SOC(t)\le SOC_{\max}(t) \tag{5}$$

Where $SOC(t)$ is the state of charge of the energy storage element at time t ;$P_{\mathrm{c}}(t)$、$P_{\mathrm{d}}(t)$ are the charging and discharging power of the energy storage element at time t ; η_{c} 、 η_{d} is the charging and discharging efficiency; ω_{c} 、 ω_{d} is the charging and discharging status indicator of the energy storage element.

2.3 Power constraints for energy storage elements

The power range of each energy storage device is limited, as shown in equation (6):

$$\begin{cases} P_{\mathrm{li,min}}\le P_{\mathrm{li}}(t)\le P_{\mathrm{li,max}} \\ P_{\mathrm{sc,min}}\le P_{\mathrm{sc}}(t)\le P_{\mathrm{sc,max}} \end{cases} \tag{6}$$

3 Optimization Configuration Method for Capacity of Three Energy Storage Systems

3.1 Particle swarm optimization algorithm with adaptive inertia weights

Particle swarm optimization algorithm is an optimization algorithm that searches for the optimal solution through multiple iterations. It has strong optimization ability in solving optimization functions. After a certain number of iterations, it can quickly locate the approximate value of the optimization function and is widely used in engineering calculations. Inertia weight coefficients are introduced into the velocity update equation α， The speed V update formula is:

$$V_{id}^{k+1} = \alpha V_{id}^{k} + c_1 r_1 (G_{id}^{k} - X_{id}^{k}) + c_2 r_2 (G_{pd}^{k} - X_{id}^{k}) \tag{7}$$

Where α is the inertia weight coefficient; The subscript i represents the particle, and d represents the dimension of velocity; The superscript k represents the number of iterations; c_1、c_2 are acceleration constants; r_1、r_2 are random numbers between 0 and 1; G_{pd} is the global optimal value searched for by the entire population; G_{id} is the individual optimal value of the particle.

3.2 HESS capacity optimization configuration

The adaptive particle swarm optimization algorithm with adaptive inertia weight was adopted to establish the optimal configuration model of the HESS. With the minimum average annual cost of the energy storage system throughout its life cycle as the optimization objective, three constraint conditions, namely energy conservation constraint, SOC constraint of each energy storage device and power constraint, were set. The configuration scheme of the energy storage device is searched and optimized in the limited interval.

The process of hybrid energy storage capacity optimization based on improved particle swarm algorithm is as follows: Firstly, the position and velocity of each particle in the particle swarm are initialized, and each particle takes a random value within the set range to initialize the individual extreme value and the global extreme value; Then update the rated power values of lithium batteries and SC; The SOC values of lithium batteries and SC in each particle are calculated to check whether the three constraint conditions of energy conservation, power constraint and state of charge are met. If the conditions are met, the objective function of the HESS optimization configuration model, namely the fitness value, is calculated, and the extreme value is updated by comparing with the individual extreme value and global extreme value in the particle swarm. Finally, it is judged whether the results converge. If the maximum number of iterations is reached or the global optimal value does not change with the iteration process, the optimization ends and the optimal solution is output. Otherwise, the cycle continues.

4 Simulated Analysis

The particle swarm optimization algorithm, which adaptively changes the inertia weight, is used to optimize the capacity configuration of the energy storage system. The improved particle swarm optimization algorithm is used to search for the capacity configuration scheme of the HESS that meets various constraints, and the scheme with the lowest annual cost in the whole life cycle is selected as the optimal configuration scheme in this paper. The storage life T is set to be 20 years; The SOC limits of lithium batteries and SC are [0.2, 0.8] and [0.05, 0.95] respectively. To simplify the calculation, the energy storage charging and discharging efficiency η_c、η_d are set to 1. The various cost unit prices of energy storage components in the whole life cycle are shown in Table 1.

Table 1. Price of each energy storage component in the LCC

Type of energy storage	lithium battery	SC
Unit power price（yuan/kW）	1200	1400
Unit capacity price（yuan/kWh）	2000	27000
Unit maintain price（yuan/kWh）	0.02	0.01
Unit price of power disposal（yuan/kW）	120	60
Unit price of capacity disposal（yuan/kW）	80	1080

In the particle swarm optimization algorithm with adaptive inertia weight, the number of particles is 40. The maximum number of iteration steps is 500; Learning factor c_1=c_2=2; The maximum and minimum inertia weights are 0.9 and 0.4 respectively. In order to prove the excellent optimization performance of the proposed adaptive inertial weight particle swarm optimization algorithm, the traditional particle swarm optimization algorithm and the adaptive inertial weight particle swarm optimization algorithm were respectively used for calculation based on the optimization objective function set in the above section. The iterative curve of the optimal individual fitness value obtained after simulation is shown in Figure 1.

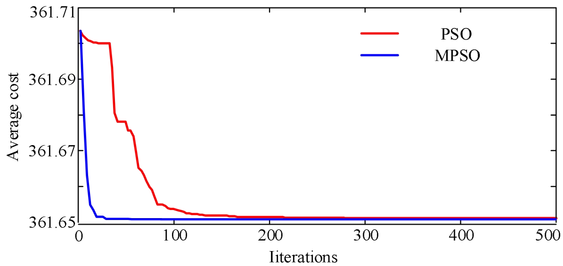

Fig. 1. Comparison of optimization effects of two particle swarm optimization algorithms

As can be seen from Figure 1, the traditional particle swarm optimization algorithm needs about 100 iterations to reach the optimal solution, while the adaptive particle swarm optimization algorithm has smooth curve transition, fast convergence speed. After 20 iterations, the fitness function basically meets the target accuracy, and the convergence speed and optimization performance are significantly improved compared with the former. The correctness and feasibility of the adaptive particle swarm optimization algorithm are verified, and it has good practicability.

The optimized load curves of the lithium battery and SC and the charge state curves of the energy storage components are shown in Figure 2 and 3 below.

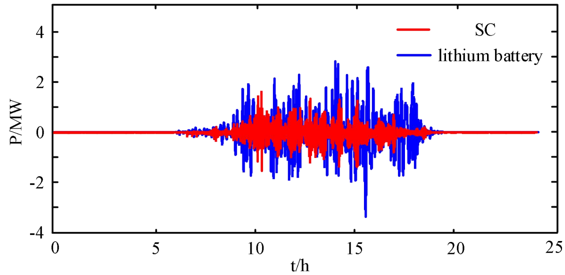

Fig. 2. Optimized energy storage component power

After optimization, the charge state of the lithium battery is within the limited range [0.2, 0.8], and the charge state of the SC is within [0.1, 0.9]. The power distribution of the hybrid energy storage among the energy storage components accords with the performance characteristics of the components, and effectively reduces the life loss of the energy storage components and improves the operation economy.

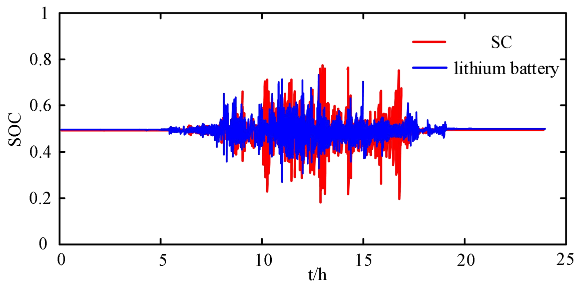

Fig. 3. Comparison of SOC of energy storage component

The optimization calculation results obtained by the optimization algorithm are shown in Table 2.

Table 2. Optimization calculation results

type of energy storage	rated power （MW）		rated capacity （MWh）		minimum annual cost （ten thousand yuan）
	lithium	super-	lithium	super-	

	battery	capacitor	battery	capacitor	
hybrid energy storage	2.78	1.14	5.56	0.19	361.6513
Single energy storage	3.92	—	7.84	—	410.4869

It is proved that this method can effectively reduce the energy storage cost and improve the overall economy of the energy storage system, and has certain reference value for engineering practice.

5 Conclusions

In this paper, SC and lithium batteries are used as hybrid energy storage devices for capacity combination optimization design, and an economic evaluation model for the full life cycle of the HESS is established. The improved particle swarm optimization algorithm is used to search for capacity configuration schemes of the HESS that meet various constraints, and the scheme with the lowest annual cost in the whole life cycle is selected as the optimal configuration scheme of this paper. Under the premise of effectively improving the convergence speed, the problem of large power abrupt change in the load curve of the energy storage components is improved, and the SOC of the energy storage components meet the requirements of the limited interval. At the same time, the total cost generated in the whole life cycle is fully considered, which has certain reference value and practical significance for the capacity allocation and economic optimization of the energy storage device in the combined optical storage system.

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