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Optimal Placement and Sizing of Hydrogen Energy Storage Power Station Considering the Uncertainty of Generation and Load

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ABSTRACT

It is a promising way to convert the excess renewable energy into hydrogen energy for storage. A two-layer optimization method considering the uncertainty of generation and load is proposed to determine the optimal placement and sizing of the hydrogen energy storage power station (HESS) in the power system with high penetration of renewable energy. The investment cost of the HESS and the operation cost of the power system with HESS are considered in the upper layer of the proposed method. Meanwhile, the Modified Backtracking Search Algorithm (MBSA) is utilized to determine the optimal placement and sizing of HESS in the upper-layer optimization. Based on the strategy formulated by the upper-layer, there is a goal that minimizes the operation cost of the power system with HESS in the lower-layer optimization. The robust optimization method is utilized to solve the optimal scheduling of the lower-layer optimization considering the uncertainty of systems. Finally, the simulation experiment in the IEEE 39-node system is performed to verify the effectiveness of the proposed two-layer optimization method. The simulation results show that the two-layer optimization method can effectively solve the optimal placement and sizing of HESS with consideration of uncertainty.

Keywords: Optimal placement and sizing; Hydrogen energy storage power station; Uncertainty; Two-layer optimization;

1. INTRODUCTION

The recent decades have witnessed a growing interest in renewable energy power generation due to the pressure of the energy crisis and environmental pollution. However, the output of renewable energy is generally constrained by natural resources, so there is an intense uncertainty in the output[1]-[2]. As the proportion of renewable energy sources such as wind power and photovoltaics increases, the consumption problem of renewable energy will become more and more prominent[3]-[4]. To further promote the consumption of renewable energy and alleviate the occurrence of power curtailment, it is necessary to build the energy storage power stations(ESS) in the power system[5]-[6].

Experts and scholars carry out many studies to calculate optimal placement and sizing of ESS. In paper [7], the optimal placement and sizing of ESS are determined by a heuristic method. Meanwhile, a neural networks method is utilized to detect the optimal placement and sizing of ESS. Aiming to minimize the investment cost and operation cost, the optimal placement and sizing of ESS in the power grid is studied in paper [8]. Furthermore, the simulation analysis is conducted by the IEEE-9 node system to verify the effectiveness of the proposed approach.

The above papers have a common feature: the energy storage systems consist of lithium battery devices. Although lithium batteries have the advantages of high energy ratio and long life [9], the high cost of this type of energy storage and the high impact of energy storage capacity by external temperature are disadvantages that limit the further promotion of lithium batteries in the power system [10]. Therefore, some scholars have researched other types of energy storage devices. In paper [11], Compressed Air Energy Storage (CAES) is applied to a microgrid system. Specifically, the cooling flow, heating flow, and power flow are considered in this system. Moreover, a bi-level optimization method is proposed to optimize the system capacity. Furthermore, to verify the performance of the bi-level optimization method, the corresponding simulations are conducted.

Hydrogen energy is an environmentally friendly renewable energy [12]. Meanwhile, hydrogen storage is cheaper than lithium batteries, and the operating status of hydrogen fuel cells is lightly affected by the ambient temperature [13]. Converting surplus renewable energy into hydrogen for storage and using hydrogen fuel cells device for power generation at the time of power shortage can reduce the impact of renewable energy on the power system and increase the consumption rate of renewable energy. The various advantages of hydrogen energy storage have made people pay more and more attention to this technology. It has increasingly become the focus of energy technology innovation and industrial support in many countries. Based on the above analysis, the optimal placement and sizing of HESS considering the uncertainty of generation and load is conducted. The key contributions of this study are shown as follows:

1) An operation mode that allows HESS offsite storage through paying network fees is proposed. Moreover, the mathematical model of optimal placement and sizing of HESS is established on this basis.
2) The uncertainty of generation and load is considered in optimal planning.
3) The two-layer optimization method is proposed to solve the optimal placement and sizing of HESS.

This paper is organized as follows: In Section II, the problem formulation of the optimal placement and sizing of HESS is given. Furthermore, in Section III, the detailed solution methodology of the problem is described. Furthermore, the case studies are performed, and the corresponding results are given in Section IV. Finally, the conclusions of this paper are summarized in Section V.

2. PROBLEM FORMULATION

A suitable placement and sizing plan of HESS can effectively promote the consumption of renewable energy [14]. Three units consist of HESS: electrolyzer (EL), hydrogen storage tank (HS), and fuel cell. Moreover, the optimal placement and sizing of HESS are more complicated than the traditional lithium battery energy. Therefore, the following objective functions and constraints are introduced to study the optimal placement and sizing of HESS considering the uncertainty:

2.1 Objective functions

Two objectives are considered in the optimization model to determine the optimal placement and sizing of HESS in the power system: the investment cost of HESS and the operation cost of the power system with HESS.

$$\min(C_{\text{invest}} + \sum_{i=1}^{N} n_i C_{\text{ope}}^i) \tag{1}$$

where C_{invest} is the investment cost of the HESS. N represents the number of typical scenarios. n_i means the number of days included in a typical scenario i. C_{ope}^i represents the operation cost of the power system with HESS in a typical scenario i.

The problem is transformed into a two-layer form to solve the above problem. The upper-layer optimization of the two-layer optimization problem aims to calculate the current optimal placement and sizing of HESS based on the operation cost calculated by the lower-layer and the investment cost of HESS. The lower-layer optimization takes the operation cost as the objective. It calculates the current optimal scheduling strategy based on the optimal placement and sizing strategy formulated by the upper-layer. The calculation method of each sub-function is introduced as follows:

For the investment cost C_{invest} of HESS, it can be calculated as follows:

$$C_{\text{invest}} = \alpha_{\text{EL}} C_{\text{EL}} + \alpha_{\text{HS}} C_{\text{HS}} + \alpha_{\text{PEMFC}} C_{\text{PEMFC}} \tag{2}$$

where C_{EL}, C_{HS}, C_{PEMFC} represent the optimal sizing of EL, HS, and Proton-Exchange Membrane Fuel Cell (PEMFC), respectively. α_{EL}, α_{HS}, and α_{PEMFC} mean the unit investment cost of EL, HS, and PEMFC, respectively.

The operating cost of the power system with HESS includes the power generation cost and operation cost of HESS. The C_{ope}^i is determined as follows:

$$C_{\text{ope}}^i = \sum_{t=1}^{T} \sum_{k=1}^{K} (a_{\text{g}} P_{t,k}^2 + b_{\text{g}} P_{t,k} + c_{\text{g}}) + \lambda_1 P_t^{\text{PEMFC}} + (\lambda_2 + \beta) P_t^{\text{EL}} \tag{3}$$

where T and K mean the scheduling period and number of the generator, respectively. a_{g}, b_{g}, and c_{g} are the cost parameters of the generator. λ_1 and λ_2 mean the operation cost of PEMFC and electrolyzer. β represents the unit cost of network fee because of the offsite storage of HESS. $P_{\text{t,k}}$ is the output power of the k_{th} generator at time t. P_t^{PEMFC} means the output power of PEMFC at time t. P_t^{EL} means the output power of electrolyzer at time t.

2.2 Constraints of optimal placement and sizing

In the optimization process of the placement and sizing, the constraint of power balancing, bus voltage, branch power, and the operation constraint of HESS need to be satisfied. The detailed constraints are shown as follows[15]:

1) The constraint of power balancing:

$$\begin{cases} P_i - V_i \sum_{i=1}^{M} V_j (G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij}) = 0 \\ Q_i - V_i \sum_{i=1}^{M} V_j (G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij}) = 0 \end{cases} \quad (4)$$

where P_i and Q_i are the power injected into node *i*, B_{ij} means the susceptance of branch *ij*.

2) The constraint of bus voltage:

The bus voltage magnitudes should be kept within acceptable operating bounds:

$$V_{m,\min} \le V_m \le V_{m,\max} \quad (5)$$

where $V_{m,\min}$ is the lower bound of the voltage limits of node *m*, and $V_{m,\max}$ means the upper bound of the voltage limits at node *m*.

3) The constraint of branch power:

$$S_n \le S_{n,\max} \quad (6)$$

where S_n represents the apparent power of branch *n*, and $S_{n,\max}$ is the maximum power allowed by branch *n*.

4) The constraint of HESS:

In the optimization process of the placement and sizing, the electrolytic operation constraints, capacity constraints of hydrogen storage tanks, and PEMFC operation constraints must be satisfied. The specific constraints are as follows[16]:

$$\begin{cases} P_{\text{EL}}^{t} \ge 0 \\ 0 \le P_{\text{EL}}^{t} \le P_{\text{EL}}^{\max} \\ C_{\text{HS}}^{0} + \eta_{\text{HS}} \sum_{t'=1}^{t} (P_{\text{EL}}^{t'} \Delta t) - \frac{1}{\eta_{\text{HS}} \eta_{\text{PEMFC}}^{\text{Ele}}} \sum_{t'=1}^{t} \left(P_{\text{PEMFC}}^{t'} \Delta t \right) \ge C_{\text{HS}}^{\min} \\ C_{\text{HS}}^{0} + \eta_{\text{HS}} \sum_{t'=1}^{t} (P_{\text{EL}}^{t'} \Delta t) - \frac{1}{\eta_{\text{HS}} \eta_{\text{PEMFC}}^{\text{Ele}}} \sum_{t'=1}^{t} \left(P_{\text{PEMFC}}^{t'} \Delta t \right) \le C_{\text{HS}}^{\max} \\ 0 \le P_{\text{PEMFC}}^{t} \le P_{\text{PEMFC}}^{\max} \end{cases} \quad (7)$$

where P_{EL}^{t} is the hydrogen produced by the EL at time *t*. $P_{\text{EL}}^{\max}$ represents the maximum output power of the EL. C_{HS}^{0} means the initial energy storage of the hydrogen storage tank. $C_{\text{HS}}^{\min}$ and $C_{\text{HS}}^{\max}$ respectively represent the minimum and maximum hydrogen storage capacity of the HS. η_{HS} represents the efficiency of the hydrogen injection process and the hydrogen release process of the HS. $P_{\text{PEMFC}}^{\max}$ is the maximum output power of the PEMFC.

3. SOLUTION METHODOLOGY

3.1 Upper layer optimization

The optimal placement and sizing of HESS is a non-linear problem. An Evolutionary Algorithm (EA) is a commonly used technical method to find the optimal solution to such problems[17]. As a special evolutionary algorithm, the performance of BSA is not sensitive to the initial parameter value of the algorithm. Therefore, the BSA is adapted to solve the problem of optimal placement and sizing of HESS. Although BSA's convergence speed and global search capability have a good performance, there is still much room for improvement. To further improve the performance of BSA in convergence speed and global search capability, a greedy crossover strategy based on excellent population guidance is used to improve the convergence speed of BSA. Only the crossover strategy-I is improved in this paper to ensure sufficient population diversity and prevent the population from falling into a locally optimal solution.

In the process of the crossover strategy-I, it is necessary to sort the population according to the fitness value first. Then, the first *p* individuals of the population are guided to the mutated population, and the way to determine *p* is as follows:

$$p = \left[0.5 * popsize * (1 - 0.5(epk - 1) / epoch) \right] \quad (8)$$

where *epk* is the iteration number of the optimization process. *epoch* means the maximum iteration number. *popsize* represents the population size.

A guided operation is required after determining the number of population individuals that need to be guided. The guiding strategy is as follows:

$$Mutant^{\text{new}} = P + (1-r) * F * (P^{\text{old}} - p) + r * (P_{bg} - P) \quad (9)$$

where *r* is the random number in the interval (0,1]. P_{bg} means the excellent population generated by the first *p* individuals of the population, and P_{bg} is a matrix of the same size as the population *P*. To ensure that P_{bg} uniformly selects the first *p* individuals in the population, the strategy selected in this paper is as follows:

Step1: Combine the sequence codes of the first *p* individuals in the population into a new set, denoted as *listp*;

Step2: Randomly sort the elements in *listp* with *k* times, and store the results after each sorting into an array *ind*, where *k*=(*popsize*/*p*);

Step3: Calculate the P_{bg} as: P_{bg}=*P*(*ind*(1:*popsize*),:);

3.2 Lower layer optimization

The primary purpose of the lower-layer optimization is to conduct the optimal dispatching of the power system with HESS. The uncertainty of the system and the optimal power flow is considered in this process. Based on the optimization strategy of placement and sizing given by the upper-layer optimization, the optimal dispatching of distribution with HESS is determined. The methods that deal with uncertain problems include stochastic optimization and robust optimization. There is no need for robust optimization to set the probability distribution function of uncertain variables compared with stochastic optimization. Instead, it uses an uncertainty set to represent the variation range of variables. Therefore, the robust optimization method is chosen in this paper to deal with the uncertainty contained in the optimal placement and sizing of HESS. The flow chart of the solution of the MBSA-based two-layer optimization method described in this paper can be shown as Fig.1:

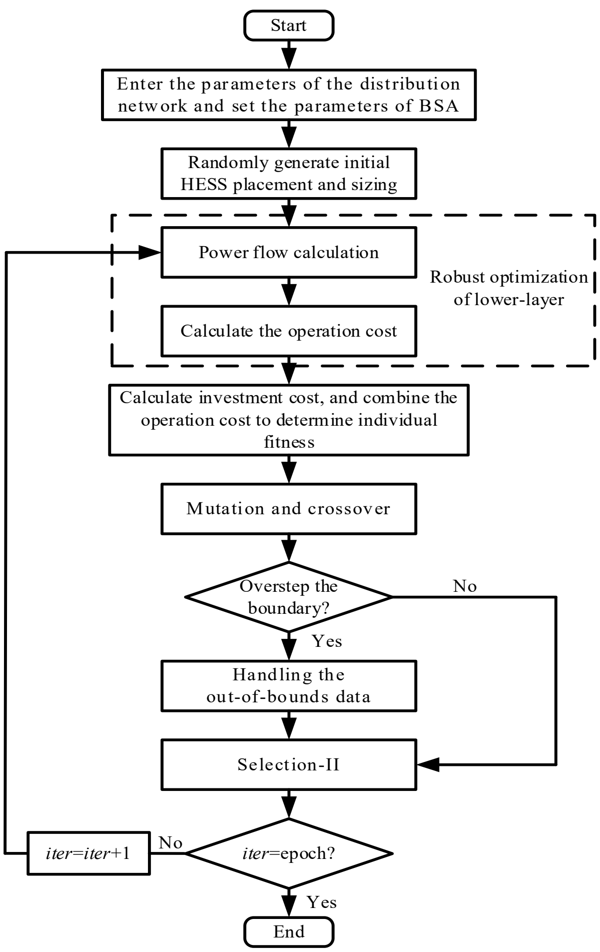

Fig.1 The flow chart of the two-layer optimization method

4. CASE STUDY

To verify the effectiveness of the MBSA-based two-layer optimization, the modified IEEE 39-node system is utilized to conduct the simulation. The topology of the modified IEEE 39-node system is shown in Fig.2.

Based on the conditions mentioned above, the optimal

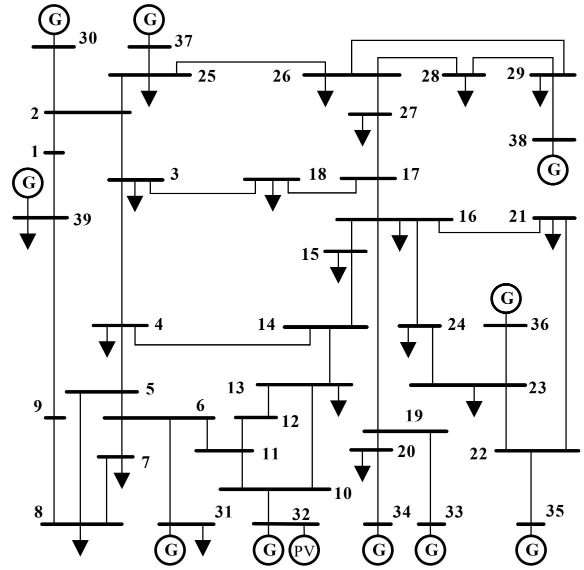

Fig.2 The topology of modified IEEE 39-node system
Comparison of algorithm performance

placement and sizing of HESS are conducted through the MBSA-based two-layer optimization and the BSA-based two-layer optimization, respectively. The optimal results of both methods are shown in Tab.1.

Tab.1 Results comparison between different algorithms

Method	Bus	EL /kW	HS /kWh	PEMFC /kW	Objective /$
MBSA-based	1	1,200	50,000	1,620	3,599,982
BSA-based	39	1,220	50,000	1,650	3,629,641

It is shown from the above table that the optimal placement and sizing of HESS calculations based on MBSA-based two-layer optimization and BSA-based two-layer optimization have different optimization results. Specifically, the objective function corresponding to the optimal strategy obtained based on MBSA-based two-layer optimization is $3,599,982, which is better than the optimal strategy obtained from BSA-based two-layer optimization.

To further illustrate the effectiveness of the MBSA-based two-layer optimization, the convergence process of the MBSA-based two-layer optimization and the BSA-based two-layer optimization are compared. The results are shown as follows:

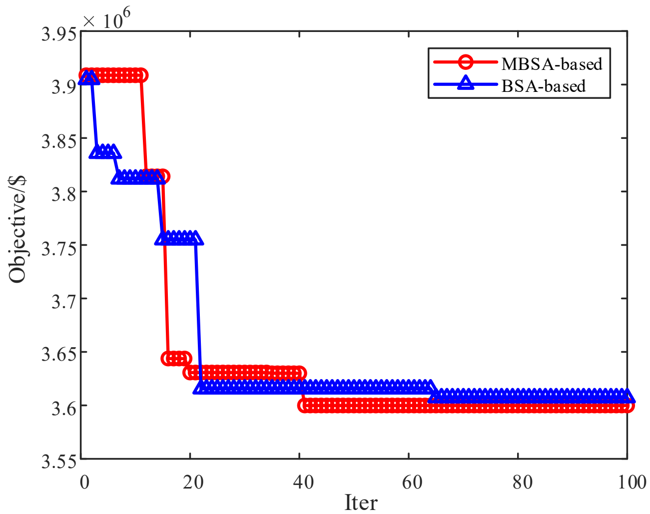

Fig.3 The convergence process of different algorithms

From Fig.3, it is demonstrated that both two-layer optimization algorithms can reach the state of convergence within the maximum number of iterations. Furthermore, the MBSA-based two-layer optimization method reached the convergence state at the 41st iteration, while the BSA-based two-layer optimization method reached convergence at the 64th iteration. Meanwhile, the convergence value of the MBSA-based two-layer optimization method is less than the BSA-based two-layer optimization method. The above results show that the MBSA-based two-layer optimization method has better convergence speed and stronger global search ability than the BSA-based one.

To analyze the role of HESS in the operation process of the power system, based on the above configuration results, a typical day of summer is taken as an example to study the optimal dispatching of the system. The power loss (PL), the peak-to-valley difference (PVD), and the voltage distribution are compared in this paper to study the impact of HESS on the original power system. The comparison results of the power loss (PL) and peak-to-valley difference (PVD) are shown as Tab.2:

Tab.2 Results of comparison between different systems

Type	PL /kW	PVD /kW
With HESS	1,994,51	2606.70
Without HESS	6,951.46	4065.20

From the above table, it can be found that the PL of the power system without HESS is 6,951.46 kW, while the PL of the power system with HESS is 1,994.51 kW. Meanwhile, the PVD of the power system without HESS is 4,065.20 kW, and the PVD of the power system with HESS is 2,606.70 kW. This calculation result shows that the integration of the HESS can decrease the power flow of the power system. Meanwhile, during the peak load period of the power system, the PEMFC of HESS can be utilized to provide electric energy to relieve the power supply pressure of the power system.

5. CONCLUSION

This study proposed a two-layer optimization method to determine the optimal placement and sizing of HESS considering the uncertainty of generation and load. Specifically, the optimal planning was determined in the upper layer by the MBSA. The optimal dispatching of the power system considering the uncertainty of generation and load was achieved by robust optimization in the lower layer. Finally, the effectiveness of the proposed two-layer method optimization was verified in the modified IEEE 39-node system. The main conclusions of this study are summarized as follows:

1) A new operating model was designed to allow HESS offsite storage by paying network fees. The feasibility of it was verified in simulation experiments.
2) A two-layer optimization method was proposed to solve the optimal placement and sizing problem of HESS. Compared with the BSA-based two-layer optimization method, the MBSA-based two-layer optimization method performed better in convergence speed and global search capability.
3) The advantages of HESS integration were verified, and the integration of HESS significantly reduced the power loss and peak-to-valley difference of the power system.

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