Energy Proceedings
Vol 40, 2024
ISSN 2004-2965

Research on Optimal Configuration of Energy Storage Capacity Considering High Proportion of Stable Photovoltaic Consumption

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ABSTRACT

To satisfy the requirements of the renewable energy systems' construction and development, as well as reducing the challenge got from large-scale renewable energy integration, this paper made some contributions based on a hydropower-photovoltaic (PV)- storage system (HPSS). The capacity ratio of storage system, hydropower and PV, is optimized aiming to smoothly utilize the renewable power output.

First of all, two application scenarios are created. One scenario is focusing on the power output smoothing effort during the piecewised time durations, which is defined as Step Output Power Scenario (SOPS) in this paper; the other scenario is power output shaving in high-frequency segment based on full-time duration. It is defined as Smooth Out the Power Fluctuation Scenario (SOPFS) in this paper. Finally, based on the above two scenarios, multi-objective energy storage capacity optimization is proposed. In addition, the integration value of each generation scheduling period in SOPS is optimized.

The measured data from hydro-PV power stations in Lancang River Energy Base is applied, which shows that the proposed method can effectively alleviate the stochastic fluctuations of the renewable energy power output. What's more, compared with the stand-alone PV system, the integration percentage of renewable energy increased by 21.45%. The HPSS which utilizes energy storage units with capacity of 1,500 MWh is more economical than the stand-alone power generation system.

Keywords: photovoltaic integration, SPOS, SOPFS, NSGA-II, energy storage capacity optimization, LCC

NONMENCLATURE

Abbreviations

HPSS	Hydropower-Photovoltaic-Storage System
LCC	Life cycle cost
LFP	Lithium Iron Phosphate
PV	Photovoltaic
PVCR	PV Curtailment Ratio
RESS	Renewable Energy Storage System
SOC	State Of Charge
SOPFS	Smooth Out the Power Fluctuation Scenario
SOPS	Step Output Power Scenario

1. INTRODUCTION

The proportion of renewable energy sources integration is increasing. However, renewable energy power generation system has volatility, resulting in wind and light abandon [1,2]. The hydro-PV power generation system can eliminate the fluctuation in output power, and effectively enhance the safety and stability of system operation [3,4]. Moreover, energy storage devices are essential for improving the safety and stability of renewable energy systems.

The electrochemical energy storage has the advantages of fast response speed and mature technology, but its usage life is short. The Lithium Iron Phosphate (LFP) battery with electrochemical energy storage technology makes up for the shortcomings of

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

traditional technology. Therefore, the LFP battery is selected as the energy storage device of the energy system in this paper.

With the widespread application of renewable energy sources, the cost is declining, creating fierce competition in the energy sector [5,6]. Hence, in order to enhance the competitiveness of the industry, it is necessary to improve the economy of renewable energy generation systems. The energy storage technology has become an effective way to solve the problem [7]. So, the rational allocation of energy storage capacity is an urgent issue.

Numerous studies have been done to enhance the economics of renewable energy generation systems. For example, a HPSS capacity optimization method is proposed to reduce the life cycle cost (LCC) [8-11]. However, besides taking into account the system's economy, it is necessary to consider the reliable performance of the system.

Due to the increasing demand, renewable energy reliability and system economic performance are often used to optimize the energy storage system capacity. For example, an optimization method of wind-PV-storage power generation system based on annual load deficit rate (LPSP) and the LCC is proposed [12]. This method not only fails to consider the stable absorption of high PV power generation proportion, but is also applied in a single scenario where the performance of the HPSS is not compared with other systems.

In recent years, intelligent algorithms and the optimization accuracy have been continuously improved. Energy storage capacity optimization typically uses high-reliability algorithms. For example, the NSGA-II algorithm is adopted to solve the built model [13,14]. Furthermore, the original power data are also divided into frequency components to enhance the accuracy of capacity optimization. For example, a low-pass filtering method is used to decompose the wind farm's active power into high-frequency and low-frequency components.

To solve the above problems, the HPSS based on multi-objective NSGA-II is established. It aims to absorb smoothly a high proportion of renewable energy sources. The main task of the thesis is to optimize its capacity. The details are as follows:

(1) In sections 2 and 3, two application scenarios are created. Moreover, the multi-objective optimal model for hydro-PV system is developed.

(2) In section 4, the operation strategy of the renewable energy system and a multi-objective storage capacity optimization method based on NSGA-II are presented. The two kinds of optimization models of independent PV-Energy storage system and the HPSS are designed.

(3) In section 5, the performances of the two optimization models in different scenarios are compared. In addition, the reliability of the multi-objective optimization model based on hydro-PV system is verified.

2. MULTI-OBJECTIVE ENERGY STORAGE OPTIMIZATION CONFIGURATION MODEL OF HYDRO-PV SYSTEM

To optimize the capacity of the HPSS, a multi-objective optimization algorithm is developed in this paper. Then, the optimization result is compared with that of the PV-Energy storage system.

2.1 The multi - objective optimization

The optimization objectives of this paper are to minimize the LCC and PV curtailment Ratio (PVCR). The specific formula is as follows:

f1:
$$LCC = ICC - \sum_{n=1}^{N} \frac{d_n}{(1+i)^n}\mathrm{tr} + \sum_{n=1}^{N} \frac{a_n}{(1+i)^n}(1-\mathrm{tr}) + \sum_{r=1}^{R} \frac{ICC_C}{(1+i)^{rl_c}}(1-\mathrm{tr}) - \frac{s}{(1+i)^N} + \mathrm{penalty} * \mathrm{M} \quad (1)$$

Where *LCC* is the initial cost of the energy storage system, d_n is the annual depreciation, a_n is the annual maintenance and operating costs, *R* is the total number of replacements over the life of the project, ICC_C is the investment cost of the parts to be replaced. L_C is the life of the part to be replaced, *s* is the salvage value. And *M* is the penalty price.

f2:
$$PVCR = \frac{\sum_{t=1}^{T} PVCR_t}{n} \quad (2)$$

$$PVR_t = \frac{PV_t - Grid\_AE_t}{PV_t} \times 100\% \quad (3)$$

Where $PVCR_t$ is the *PVCR* at time *t*, PV_t is the PV power at time *t*, and $Grid\_AE_t$ is the power absorbed of the power grid at time *t*. The specific parameters are shown in Table 1 [15,16].

Table. 1 Economic parameters table

Name	Parameters
Battery cost (RMB /Wh)	1.1
Inverter cost (RMB/Wh)	0.2
Other expenses of energy storage system (RMB /Wh)	0.5

Project life (N) (years)	25
Battery life (years)	8
Inverter life (years)	10
Tax rate (tr)	0.05
Interest rate (i)	0.07
Annual maintenance and operating cost factor	0.08
Penalty electricity price (RMB /KWh)	0.5

2.2.1 SOC constraints

To extend the battery lifecycle and ensure the normal operation of the energy storage system, it is essential to constrain the state of charge (SOC) and the output power of the energy storage system.

$$P_{min} \le P(t) \le P_{max} \tag{4}$$

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

2.2.2 The output power balance constraints

$$P_{grid}(t)=P_{pv}(t)+P_{hydro}(t)+P_{ess}(t) \tag{6}$$

Where $P_{grid}(t)$, $P_{PV}(t)$, $P_{hydro}(t)$ and $P_{ess}(t)$ are respectively the integration, the PV, the hydroelectric and the energy storage system output power at the time t.

2.2.3 The capacity constraints

$$C_{ess\min}(t) \le C_{ess}(t) + C_{ess\max}(t) \tag{7}$$

$C_{ess}(t)$ is the capacity energy storage system in the optimization process.

2.2.4 The energy storage balance constraints

$$SOC_{bat}(t) = SOC_{bat}(t-1)(1-\sigma_{sd}(t)) + \left[P_{PV}(t) - \frac{P_{load}(t)}{\eta_{inv}}\right]\eta(charging) \tag{8}$$

$$SOC_{bat}(t) = SOC_{bat}(t-1)(1-\sigma_{sd}(t)) + \left[\frac{P_{load}(t)}{\eta_{inv}} - P_{PV}(t)\right]\eta(discharging) \tag{9}$$

Where σ_{sd} is the self-discharge ratio per hour, P_{load} is the load power, η_{inv} is the inverter efficiency.

2.2.5 Hydropower output constraint

$$H_{it}^{\min} < H_{it} < H_{it}^{\max} \tag{10}$$

Where H_{it} is the output power of the i-th hydropower station at the time t.

3. APPLICATION SCENARIO

3.1 Step Output Power Scenario (SOPS)

The Step Output Power Scenario means that the output power of the renewable energy storage system (RESS) is fixed at each time stage. The fixed value is the planned integration value, which is the average output power of the RESS at a fixed time interval. The calculation formula is as follows:

$$Gird=\frac{power_1+power_2+.....+power_n}{n} \tag{11}$$

Where, *Gird* is the planned integration value.

3.2 Smooth out the power fluctuation scenario (SOPFS)

Low-pass filter is widely used in data processing for renewable energy fluctuation suppression [17]. Thus, the low-pass filter method is adopted in this paper. The smooth curve after filtering is the planned integration curve. Introduction presents background information on the objectives, research questions and scope/limitation of the paper.

To ensure the authenticity of data and reduce the energy system's PVCR, the low-pass Butterworth filter is utilized in this paper. A Butterworth low-pass filter model is established in this paper. First, a suitable transfer function is selected to attenuate the high-frequency component of the wind PV output power; then, the desired smooth curve is obtained by inverse transformation. The equations are as follows:

$$H(u,v)=\frac{1}{1+\left[\frac{D(u,v)}{D_0}\right]^{2n}} \tag{12}$$

Where D_0 is the distance between the Cut-off frequency and the origin, $D(u,v)$ is the distance of the point and the origin.

4. SYSTEM OPERATION STRATEGY

NSGA-II can reduce the complexity of NSGA. In addition, the algorithm has fast running speed and good convergence. An improved NSGA-II is developed to optimize the capacity of the HPSS in this paper.

4.1 Strategy of energy storage system operation

The concrete process is shown in Fig. 1. The energy storage system is discharged, when the integrated output power is less than the planned integrated power. Besides, the energy storage system is charged when the integrated output power is higher than the planned integration power.

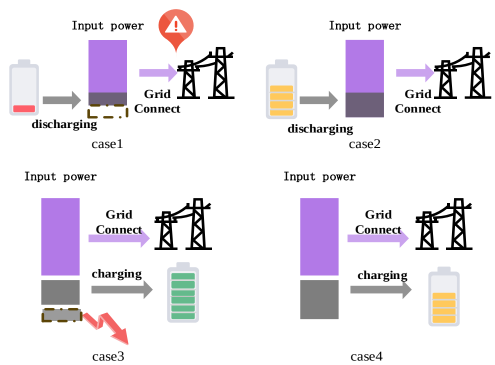

Fig. 1 Four states of energy storage operation

4.2 Application Scenario Operation strategy

As shown in Fig. 2, the two scenarios are created and the steps of the optimization process are various.

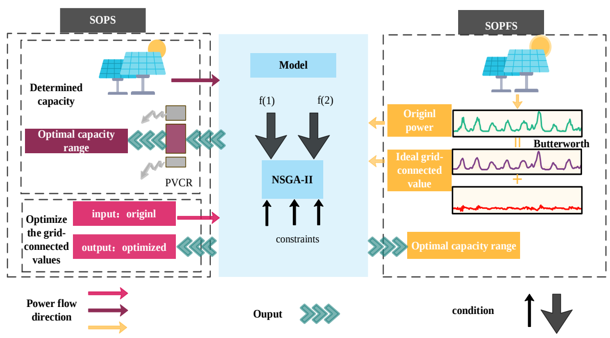

Fig. 2 The chart of application scenario operation strategy

4.2.1 SOPS

The optimization process of SPOS is decomposed into two steps. In the first step, according to the optimal PVCR of the HPSS, the optimal range of capacity is determined. In the second step, the integrated HPSS values are processed for economic optimization.

4.2.2 SOPFS

Firstly, the original output power of the PV power station is obtained. Secondly, the Butterworth low-pass filter model is established; and the planned integration value of the HPSS is obtained by filtering. Finally, the capacity of the HPSS is optimized according to fitness functions and constraints.

5. ANALYSIS OF NUMERICAL EXAMPLES

The HPSS base is studied as a case in this paper. In the early stage, PV power station with an installed capacity of 10,000 MW is constructed. Then, in line with the project schedule, the capacity design of PV power station and the final HPSS scale are optimized. The output power is shown in Fig. 3:

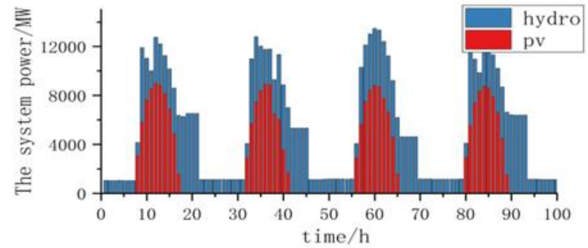

Fig. 3 The diagram of PV output power about the energy system

5.1 Capacity optimization of PV-Energy storage system

5.1.1 SOPS

(1) Determine the optimal range of the capacity

In this paper, NSGA-II optimization algorithm is used to determine the range of energy storage capacity.

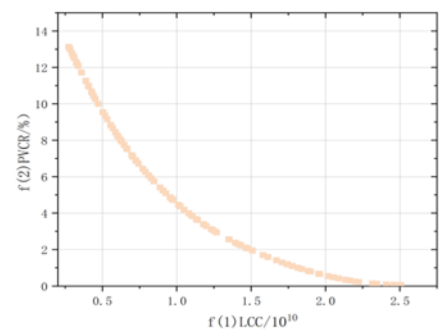

Fig. 4 Diagram for multi-objective optimization iterations

As shown in Fig. 4, the high-density optimization of the planned integration value is the most appropriate when the capacity of the energy storage system ranges from 500 MWh to 2000 MWh. What's more, to compare the impact of energy storage capacity on energy system performance in two application scenarios, a storage system capacity of 0 MWh is considered.

(2) Calculate of integration values and high-density optimization parameters

The energy storage system capacity is chosen as 0 MWh, 500 MWh, 1000 MWh, 1500 MWh and 2000 MWh respectively in this paper. Then, the planned integration values of PV-Energy storage systems equipped different capacities are optimized. After optimizing the integration values, the LCC and the PVCR are shown in Table 2.

Table. 2 The optimization result table

Capacity/MWh	LCC/million	PVCR/%
0	57.80	22.43
500	2.59E+05	14.60
1000	5.17E+05	8.84
1500	7.75E+05	5.47
2000	1.03E+06	3.51

As can be seen from Table 2, when the capacity of the PV-Energy storage system is increased from 0 MWh to 500 MWh, the PVCR is reduced by 7.83%. In addition, the electricity penalty is 57,800 RMB without the storage system. This indicates a lack of power to the system.

As shown in Fig. 5, when the capacity is 1000 MWh, the three types of the PV-Energy storage system's output power of are compared. The comparison further confirms the lack of electricity. So that, the installation of the energy storage system is crucial for renewable energy system.

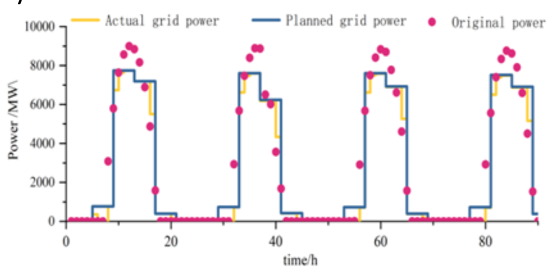

Fig. 5 Chart of PV-Energy Storage System Output Power Comparison

<u>5.1.2 Smooth power fluctuation scenario</u>

(1) Original data processing-Butterworth filter

As can be seen in Fig. 6, the PV power curve is smoother after passing through the Butterworth low-pass filter.

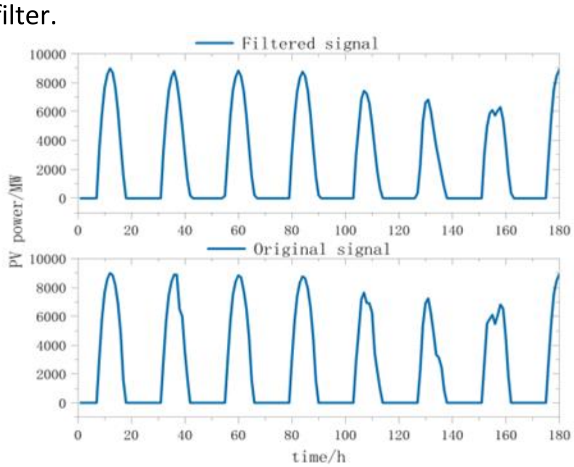

Fig. 6 Diagram of pre-filtered and post-filtered power

(2) Multi-objective optimization and the system parameters calculation

After low-pass filter optimization, the LCC and the PVCR are obtained. The results are shown in Table 3.

Table. 3 Performance parameters of the PV-Energy storage systems equipped different capacities

Capacity/MWh	LCC/million	PVCR/%
0	1.62 E+03	4.23
500	2.97E+05	3.25
1000	5.48E+05	2.76
1500	8.00E+05	2.18
2000	1.05E+06	1.39

As can be seen in Table 3, the energy storage system reduces the PVCR of the energy system, but increases the LCC. Furthermore, the penalty price is 16.2 million RMB when it is not equipped with an energy storage device. This indicates that the energy system has a serious power shortage problem.

<u>5.1.3 Comparative analysis of two application scenarios</u>

By comparing Table 2 and Table 3, it can be seen that when the energy storage system is not equipped, the PVCR in the SOPFS is lower than that in the SOPS. The power shortage in SOPFS is more serious than that in SOPS. The reasons are as follows:

(1) In the process of optimizing the integration values in SOPS, the main task is economic evaluation, and the auxiliary task is PVCR.

(2) The planned integration values curve in SOPFS coincides better with the original photovoltaic power curve, and PVCR is lower. However, the delay in the filter power curve is caused by the filter phase. Hence, the high lack of electricity leads to a poor economy.

The real-time PVCR curves of the energy system in different application scenarios is shown in Fig. 7.

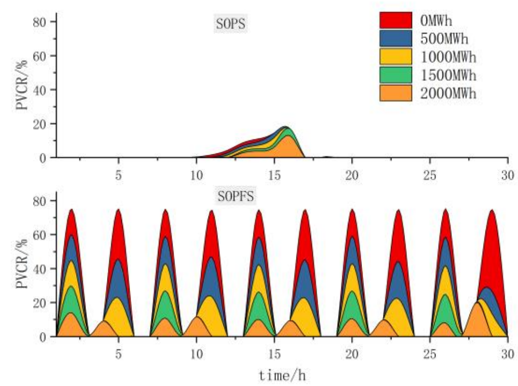

Fig. 7 Real-time change of the PVCR in two scenarios

In both scenarios, the PVCR can be effectively reduced with the increase of storage capacity, but the trend of PVCR reduction is lower in SOPS. In addition, the LCCs of the systems with the same capacity are relatively close in both scenarios. The results show that the economy and reliability of the energy storage system are better in SOPS. Therefore, the SOPS is considered to optimize the capacity of the HPSS in this paper.

5.2 The capacity optimization of the HPSS

The installed capacity of hydropower and PV are 9525 MW and 10000 MW respectively in this paper. Then, combined with the real-time output power of the renewable energy system, the energy storage system capacity of the HPSS is optimized.

Table. 4 The chart of optimization results comparison

capacity /MWh	LCC/million RMB		PVCR/%	
	original	optimized	original	optimized
0	1.57E+03	1.56E+03	0.86	0.89
500	4.30E+03	4.30E+03	0.66	0.69
1000	6.80E+03	6.80E+03	0.5	0.53
1500	9.36E+03	9.34E+03	0.4	0.43
2000	1.20E+04	1.18E+04	0.33	0.36

By comparing the parameters in Table 4, when the energy storage system capacity is 1500 MWh, the optimized LCC of the HPSS is reduced by 20 million RMB. It can be seen that in the second step of the optimization process in SOPS, taking economy as the dominant factor can enhance the economy of the energy system. It also proves the reliability of optimization. In addition, the analysis shows that the HPSS is more economical and practical.

6. CONCLUSIONS

A multi-objective energy storage capacity optimization model based on NSGA-II is proposed in this paper. It is used to optimize the energy storage system capacity in the PV-Energy storage system and the HPSS. The specific conclusions are as follows:

(1) When the energy storage system capacity is increased from 0 MWh to 500 MWh, the PVCR in the SOPS is reduced by 7.83%, and the PVCR in SOPFS is reduced by 0.98%. It is shown that when the energy storage system is equipped, the PVCR is reduced more in SOPS.

(2) When the energy storage is not equipped in the PV system, the PVCR in SOPS is 18.2% higher than that in SOPFS. In addition, the LCC in SOPS is 1.042 million RMB higher than that in SOPFS. It is shown that the power shortage in SOPFS is more serious than in SOPS.

(3) When the energy storage capacity is 1500 MWh, the original LCC in the HPSS is 20 million RMB higher than the optimized LCC. It shows that the high-density integration value optimization model based on NSGA-II can effectively improve the system economy.

ACKNOWLEDGEMENT

This work was supported in part by National Key R&D Program of China under Grant 2019YFE0118400.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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