Research on hybrid energy storage capacity allocation of photovoltaic power station based on energy storage selection and carbon income

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Abstract. To reduce the impact of intermittence and volatility of photovoltaic power station (PPS) on the power grid, energy storage system (ESS) is often introduced to stabilize the output power fluctuation. In response to the low-carbon development process and considering the limitations of using fixed hybrid energy storage system (HESS) combinations for capacity optimization research, this paper proposes a HESS capacity configuration method for PPS considering energy storage selection and carbon benefits. Firstly, the wavelet packet decomposition method is used to decompose the power generation of PSS, and the high-frequency fluctuation component that needs to be stabilized by ESS is obtained. Then, an optimal operation model of HESS for PPS is established. The model considers the selection of HESS and the carbon benefits of PPS. With the goal of maximizing the net profit of the system in the whole life cycle, the model is modeled in the YALMIP toolbox and the CPLEX solver is used to solve the model to complete the selection of HESS and the optimal configuration of capacity. Taking the measured data of a PPS in China as an example for simulation, it is concluded that the HESS composed of vanadium battery and super capacitor is the optimal combination scheme, and the two can better play the complementary role.

Keywords: Photovoltaic Power Stations, Energy Storage Selection, Carbon Earnings, Capacity Configuration.

1. Introduction

With the proposal of the dual-carbon target, PPS have developed well. However, the power of PPS is fluctuating and intermittent, and large-scale direct grid connection will affect the safe operation of power system. At present, the HESS is often used to stabilize the output power fluctuation of PPS, so that the photovoltaic power generation becomes 'controllable and adjustable' [1]. However, the cost of configuring ESS in PPS is high, so it is important to create a reasonable energy storage capacity configuration scheme to improve the economy of PPS.

Abdalla A A et al. [2] used HESS to realize the smoothness of output power of PPS. In [3], a HESS composed of battery, supercapacitor and fuel cell is used to reduce the power fluctuation of PPS. Karunanithi K et al. [4] proposed a HESS composed of supercapacitors and lithium batteries. Supercapacitors can release their energy because they can discharge large currents in a shorter time, lithium batteries are responsible for providing the required energy for the load to achieve the effect of balancing power. The above research is based on the HESS combination given to study the capacity configuration of HESS. Although it has a certain stabilizing effect on the output power of HESS, it does not consider the different effects of different types of HESS combinations on the energy storage capacity configuration and the economy of PPS. And the above research did not consider the participation of photovoltaic electric field in the carbon trading market for profit, and its investment reference value did not fully consider the future development trend of low-carbon electricity market transactions.

In view of the above problems, this paper aims to propose a HESS capacity configuration method for PPS considering energy storage selection and carbon benefits. This method considers the selection of HESS and the carbon income of PPS and establishes an optimal operation model. With the goal of maximizing the net income of the system in the whole life cycle, the selection of ESS and the optimal configuration of capacity are completed.

2. The Power Smoothing Strategy of PPS Based on HESS

2.1. ESS grid-connected structure

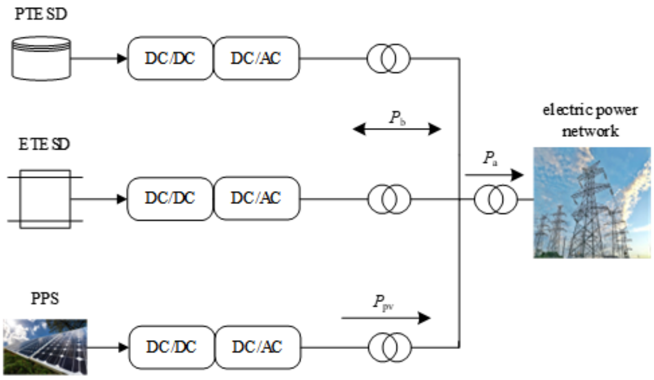


Figure 1. ESS grid-connected structure.

ESS can be divided into energy-type energy storage devices (ETESD) and power-type energy storage devices (PTESD) [5]. In this paper, a HESS composed of ETESD and PTESD is used to stabilize the output power fluctuation of PPS to meet the grid-connected requirements, as shown in Figure.1. P_{pv} is the output power of PPS; P_a is the grid-connected power of PPS; P_b is the fluctuating power of PPS, this part needs HESS for response processing.

$$P_{pv} = P_a + P_b \tag{1}$$

2.2. Decomposition of Photovoltaic Power Generation by Wavelet Packet Method

Wavelet packet decomposition (WPD) is an advanced signal processing tool [6], which is mainly used to analyze non-stationary signals. Through wavelet packet, the high-frequency fluctuation component and the low-frequency grid-connected component are obtained in PPS.

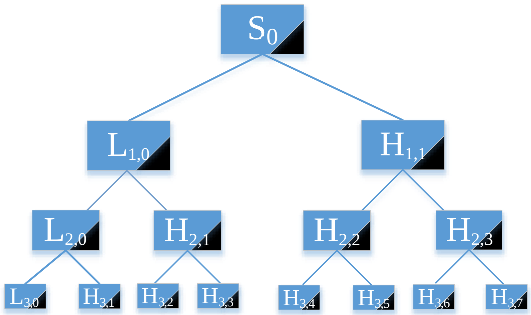


Figure 2. Schematic diagram of the WPD process.

The principle of WPD is shown in Figure.2. S_0 is the initial data, and it is decomposed to obtain the low-frequency component $L_{1,0}$ and the high-frequency component $H_{1,1}$, and then the two components are continuously decomposed. The frequency increases from left to right, and the leftmost L component is the lowest frequency component. The hierarchical decomposition is until the active power change rate corresponding to the L component meets the requirements of the current national standard. Currently, the corresponding high-frequency fluctuation component is the power that the PPS needs to stabilize. According to the requirements of the national standard [7], the active power change rate of the grid-connected does not exceed 10% rated capacity/min. In this paper, the fluctuation rate of the grid-connected power of PPS at 1 min level is used as the criterion.

$$\varphi = \frac{\left| P_b(t+1) - P_b(t) \right|}{W_{pv}} \times 100\% \le 10\% \tag{2}$$

In the formula, φ is 1min level fluctuation rate; W_{pv} is the installed capacity of PPS.

3. The Mathematical Model of HESS and Power Allocation Strategy

3.1. HESS Selection

This paper chooses four kinds of HESS combination schemes to study the selection and capacity configuration of ESS. The combination schemes in Table 1.

Table 1. HESS combination scheme.

scheme	ETESD		PTESD	
	Lithium battery	Vanadium battery	Super capacitor	Flywheel
1	✓		✓	
2	✓			✓
3		✓	✓	
4		✓		✓

3.2. Mathematical Model of HESS

$$E_{\mathrm{e}}(t)=[\eta_{\mathrm{e}}\sum_{t=1}^{T}P_{\mathrm{ech}}(t)X_{\mathrm{e}}(t)\Delta t-\frac{\sum_{t=1}^{T}P_{\mathrm{edis}}(t)Y_{\mathrm{e}}(t)\Delta t}{\eta_{\mathrm{e}}}] \tag{3}$$

$$E_{\mathrm{p}}(t)=[\eta_{\mathrm{p}}\sum_{t=1}^{T}P_{\mathrm{pch}}(t)X_{\mathrm{p}}(t)\Delta t-\frac{\sum_{t=1}^{T}P_{\mathrm{pdis}}(t)Y_{\mathrm{p}}(t)\Delta t}{\eta_{\mathrm{p}}}] \tag{4}$$

In above formula, $E_{\mathrm{e}}(t)/E_{\mathrm{p}}(t)$ is cumulative charge and discharge power of the ETESD and PTESD from the beginning to the time t through the corresponding converter ; t refers to the system operation cycle ; $X_{\mathrm{e}}(t)/X_{\mathrm{p}}(t)$ and $Y_{\mathrm{e}}(t)/Y_{\mathrm{p}}(t)$ are charge-discharge states of the ETESD and PTESD at time t. $P_{\mathrm{ech}}(t)/P_{\mathrm{pch}}(t)$ and $P_{\mathrm{edis}}(t)/P_{\mathrm{pdis}}(t)$ are the charge and discharge power of ETESD and PTESD at time t. $\eta_{\mathrm{e}}/\eta_{\mathrm{p}}$ refers to the charge and discharge efficiency of ETESD and PTESD connected to external grid through corresponding converter.

$$\eta_{\mathrm{e}}=\eta_{\mathrm{e}}^{\mathrm{self}}\eta_{\mathrm{DC/DC}}\eta_{\mathrm{DC/AC}} \tag{5}$$

$$\eta_{\mathrm{p}}=\eta_{\mathrm{p}}^{\mathrm{self}}\eta_{\mathrm{DC/DC}}\eta_{\mathrm{DC/AC}} \tag{6}$$

In above formula, $\eta_{\mathrm{e}}^{\mathrm{self}}/\eta_{\mathrm{p}}^{\mathrm{self}}$ is the charge-discharge efficiency of ETESD and PTESD itself; $\eta_{\mathrm{DC/DC}}$ is the efficiency of ESS through the DC/DC converter; $\eta_{\mathrm{DC/AC}}$ is the efficiency of ESS through the DC/AC converter.

$$SOC_{\mathrm{e}}(t)=SOC_{\mathrm{e}}(0)+\frac{E_{\mathrm{e}}(t)}{Q_{\mathrm{e}}} \tag{7}$$

$$SOC_{\mathrm{p}}(t)=SOC_{\mathrm{p}}(0)+\frac{E_{\mathrm{p}}(t)}{Q_{\mathrm{p}}} \tag{8}$$

In above formula, SOC is the state of charge, and $SOC_{\mathrm{e}}(0)/SOC_{\mathrm{p}}(0)$ is the SOC at the beginning of the ETESD and PTESD. $Q_{\mathrm{e}}/Q_{\mathrm{p}}$ is rated capacity of the ETESD and PTESD.

3.3. Power allocation strategy of HESS

When the HESS needs to absorb the fluctuating power of PPS at this time, it starts charging first with the help of the large capacity of ETESD. When its maximum charging power cannot meet the fluctuating power of PPS, it is charged by the PTESD. When the HESS needs to supplement the fluctuating power of PPS at this time, the rapid discharge characteristics of the PTESD allow it to start discharging first, to ensure that it has sufficient capacity to be stored before the next charge. When the maximum discharge power cannot meet the fluctuating power of PPS, the ETESD is used for discharge replenishment. Figure 3 is the power allocation strategy of HESS.

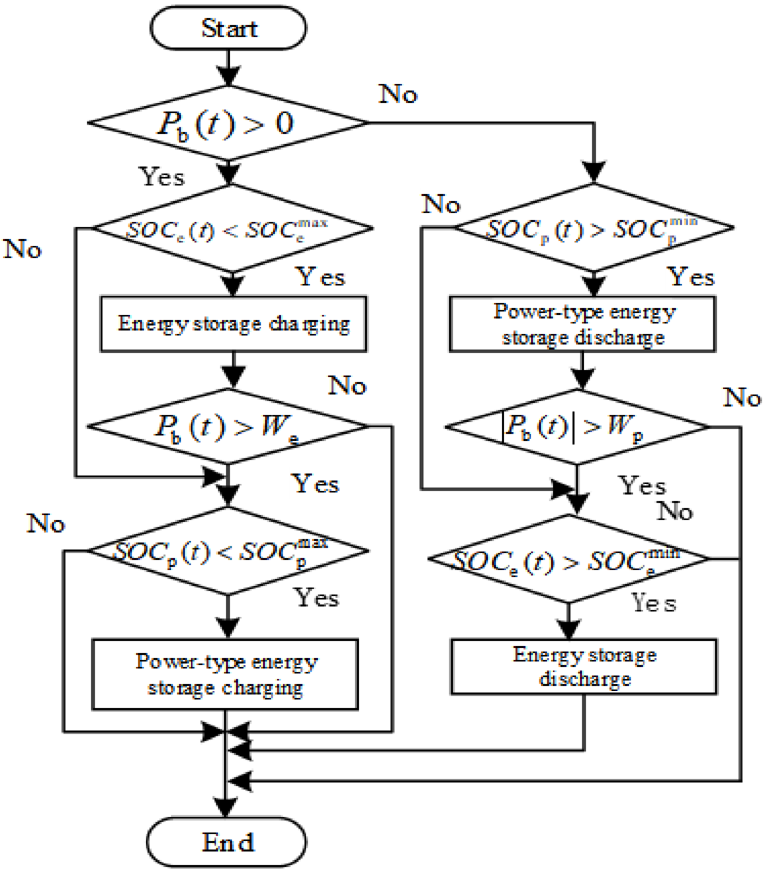


Figure 3. Power allocation strategy of HESS.

4. Optimized Operation Model of HESS in PPS

4.1. Objective Function

The maximum net profit of the HESS of PPS in the whole life cycle is taken as the optimization objective. The objective function is:

$$\max I = \sum_{i=1}^{3} I_i - \sum_{j=1}^{3} C_j \tag{9}$$

In the formula, I_i is the i th income of HESS of PPS; C_j is the j th cost of HESS of PPS.

(1) Electricity sales revenue of PPS

$$I_1 = \sum_{y=1}^{Y} 365 c_e P_a (1+r)^{-y} \tag{10}$$

In above formula, Y is the whole life cycle of HESS of PPS; r is the discount rate; c_e is the on-grid price of PPS.

(2) Recovery of residual income

$$I_2 = \sigma C_1 (1+r)^{-Y} \tag{11}$$

C_1 is the initial investment cost of HESS; σ is the recovery rate of residual value, generally take 3 % -5 % [8], this paper takes 4 %.

(3) Carbon gains

The carbon emission trading mechanism is a scheme for allocating carbon emission quotas to power generation enterprises. In carbon trading, enterprises have the right to freely trade carbon emission quotas. Once their actual carbon emissions are lower than the allocated amount, they can sell excess quotas and make profits from them [9]. Especially for photovoltaic power plants, because their carbon emissions are negligible, thermal power companies can meet their carbon emission quota requirements by making compensation transactions for carbon emission reductions to photovoltaic power plants. Through this carbon trading mechanism, enterprises can control carbon emissions and obtain economic incentives but also promote the development of clean energy and reduce greenhouse gas emissions. The carbon benefits of PPS are:

$$I_3 = \sum_{y=1}^{Y} 365\delta a P_{\mathrm{a}} (1+r)^{-y} \tag{12}$$

In the formula, a is the carbon emission quota per unit of electricity; δ is the carbon trading price.

(4) Initial investment cost

$$C_1 = c_{\mathrm{ew}} W_{\mathrm{e}} + c_{\mathrm{ee}} Q_{\mathrm{e}} + c_{\mathrm{pw}} W_{\mathrm{p}} + c_{\mathrm{pe}} Q_{\mathrm{p}} \tag{13}$$

In the formula, c_{ew} and c_{pw} are the unit power cost of the ETESD and PTESD; W_{e} and W_{p} are the rated power of the ETESD and PTESD. c_{ee} and c_{pe} are the unit capacity cost of the ETESD and PTESD.

(5) Operation and maintenance costs

$$C_2 = \sum_{y=1}^{Y} (c_{\mathrm{ewo}} W_{\mathrm{e}} + c_{\mathrm{pwo}} W_{\mathrm{p}})(1+r)^{-y} + \sum_{y=1}^{Y} 365(c_{\mathrm{eeo}} E_{\mathrm{e}} + c_{\mathrm{peo}} E_{\mathrm{p}})(1+r)^{-y} \tag{14}$$

In the formula, c_{eeo} and c_{peo} are the unit capacity operation and maintenance costs of the ETESD and PTESD; c_{ewo} and c_{pwo} are the annual unit power operation and maintenance costs of the ETESD and PTESD; E_{e} and E_{p} are the total charge and discharge capacity of the ETESD and PTESD in a day.

(6) Disposal cost

$$C_3 = [(c_{\mathrm{ewP}} W_{\mathrm{e}}) + (c_{\mathrm{eep}} Q_{\mathrm{e}}) + (c_{\mathrm{pwP}} W_{\mathrm{p}}) + (c_{\mathrm{pep}} Q_{\mathrm{p}})](1+r)^{-Y} \tag{15}$$

In the formula, c_{ewp} is the unit power scrapping cost of ETESD; c_{eep} is the scrapping cost per unit capacity of ETESD; c_{pwp} is the unit power scrap cost of PTESD; c_{pep} is the unit capacity scrapping cost of PTESD.

4.2. Constraint Condition

(1) ETESD constraint

$$\begin{cases} SOC_{\mathrm{e}}^{\min} \le SOC_{\mathrm{e}}(t) \le SOC_{\mathrm{e}}^{\max} \\ X_{\mathrm{e}}(t) Y_{\mathrm{e}}(t) = 0 \\ X_{\mathrm{e}}(t), Y_{\mathrm{e}}(t) \in \{0,1\} \\ 0 \le P_{\mathrm{ech}}(t) \le W_{\mathrm{e}} \\ 0 \le P_{\mathrm{edis}}(t) \le W_{\mathrm{e}} \end{cases} \tag{16}$$

$SOC_{\mathrm{e}}^{\max}$ and $SOC_{\mathrm{e}}^{\min}$ are the upper and lower bounds of SOC; charging and discharging state constraints are added so that it is not in the charging or discharging stage at the same time; in order to avoid excessive charging and discharging of ETESD, the charging and discharging power constraint is also added.

(2) PTESD constraint

Similar to ETESD, PTESD also have *SOC*, charge-discharge state, and charge-discharge power constraints as follows:

$$\begin{cases} SOC_{\mathrm{p}}^{\min} \le SOC_{\mathrm{p}}(t) \le SOC_{\mathrm{p}}^{\max} \\ X_{\mathrm{p}}(t)Y_{\mathrm{p}}(t) = 0 \\ X_{\mathrm{p}}(t), Y_{\mathrm{p}}(t) \in \{0,1\} \\ 0 \le P_{\mathrm{pch}}(t) \le W_{\mathrm{p}} \\ 0 \le P_{\mathrm{pdis}}(t) \le W_{\mathrm{p}} \end{cases} \tag{17}$$

5. Example Simulation

5.1. Scene Simulation

Takes a PPS as an example to explore the configured energy storage capacity. The installed capacity of PPS is 35 MW. The measured output data of a typical day is shown in Figure. 4. The unit sampling time in the curve is 1 min, and the total time is 1 day.

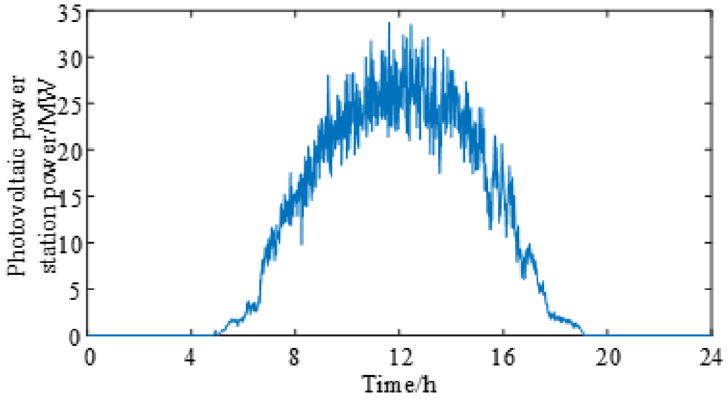
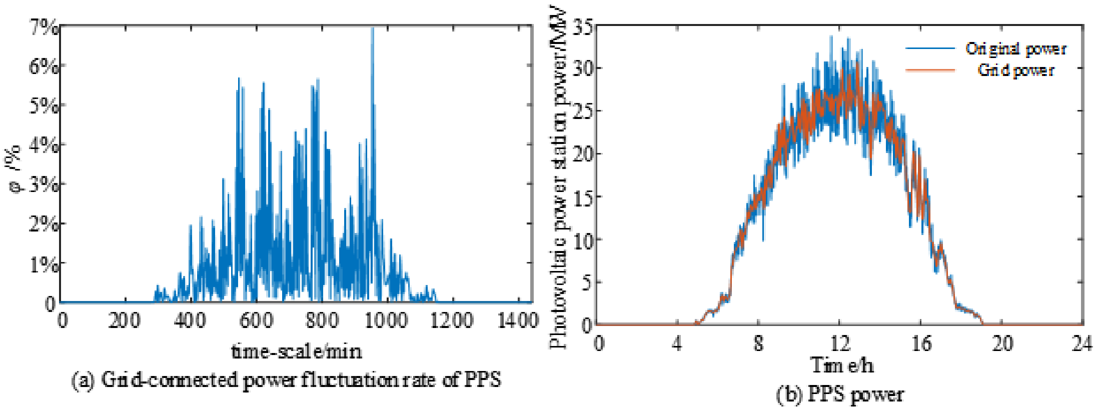


Figure 4. Output power of PPS.

The WPD is used to decompose the output power of PPS. When the number of decomposition layers is 2, the fluctuation rate φ of low-frequency grid-connected power of PPS at the 1 min level meets the national grid-connected requirements, as shown in Figure 5.



(a) Grid-connected power fluctuation rate of PPS

(b) PPS power

Fig 5. Output power decomposition of PPS.

The whole life cycle of HESS equipped with PPS is designed according to 20 years, and the discount rate is 8%. The carbon trading price is 50 CNY/t, the carbon emission quota per unit of electricity [10] is 0.5703 kg/(kW·h), and the on-grid price of PPS [11] is 0.3731CNY/(kW·h). This paper models in the YALMIP toolbox and calls the CPLEX solver to solve the model. The parameters of ESS and other equipment used in established model [12] are shown in Table 2.

Table 2 Equipment parameters

	lithium battery	vanadium battery	super capacitor	flywheel
Unit power cost/(CNY/kW)	9300	9300	1860	2170
Unit capacity cost/(CNY/kW·h)	9300	10000	12400	31000
Unit power operation and maintenance cost/[CNY/(kW·year)]	155	124	80.6	111.6
Unit capacity operation and maintenance cost/(CNY/kW·h)	0.01407	0.0134	0.0134	0.0134
Unit capacity replacement cost/(CNY/kW·h)	9300	10000	12400	31000
Unit power scrap cost/(CNY/kW·h)	465	500	93	108.5
Unit capacity scrapping cost/(CNY/kW·h)	0	0	0	0
charge discharge efficiency	0.85	0.75	0.95	0.96
SOC upper and lower limits	0.15-0.85	0.2-0.8	0.1-0.9	0.1-0.9
DC-DC efficiency	0.95	0.95	0.95	0.95
DC-AC efficiency	0.95	0.95	0.95	0.95

5.2. Simulation Results Analysis

The access capacity of PPS equipped with four HESS combinations is optimized, and the carbon income of PPS in the whole life cycle and the optimal combination and access capacity of HESS are obtained. Table 3 is the simulation results. Considering that the carbon income of PPS is related to grid-connected power, the net income of the whole life cycle of PPS is mainly related to the cost of ESS. From the following table, compared with other ESS schemes, when PPS chooses scheme 3, PPS has the largest net income in the whole life cycle. Vanadium battery and super capacitor are the best combination scheme. In addition, compared with PTESD, the capacity of ETESD is much higher, which not only makes up for the shortcomings of low energy density of PTESD, but also greatly reduces the cost of ESS capacity.

Table 3. Simulation results under different schemes.

scheme	W_e/kW	E_e/kW·h	W_p/kW	E_p/kW·h	I_3/CNY	I/CNY
1	1670.1	3486.7	13866.3	86.904	4.82×10^8	6.49×10^9
2	1675.8	3498.6	13692.7	85.816	4.82×10^8	6.43×10^9
3	1670.1	3486.7	13866.3	86.904	4.82×10^8	6.51×10^9
4	1692.9	3534.3	13627.6	85.408	4.82×10^8	6.45×10^9

Figure.6 shows the SOC of vanadium battery and supercapacitor in scheme 3. From the diagram, the SOC fluctuation range and rate of the super capacitor are large, and the SOC reaches the upper limit of 0.9. However, because the super capacitor has fast charging and discharging characteristics and high cycle times, there is no over-discharge and over-charging problem, and the large SOC fluctuation has little effect on its service life. The SOC fluctuation range and rate of vanadium battery are small, basically stable within 0.2 ~ 0.3, which is conducive to reducing the number of cycles of vanadium batteries and delaying their aging speed.

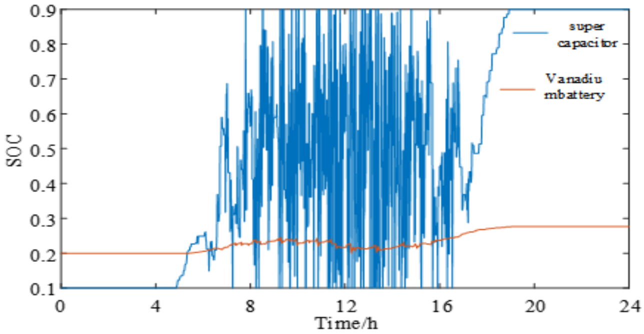


Figure 6. Vanadium battery and supercapacitor SOC.

6. Conclusions

The HESS composed of ETESD and PTESD can comprehensively complement the advantages of both. It can overcome the shortcomings of small capacity of PTESD, reduce the number of cycles of ETESD and prolong its service life.

The HESS composed of vanadium battery and super capacitor is the best combination scheme. The optimal capacity configuration results are as follows: the rated power of vanadium battery is 1670.1 kW, and the rated capacity is 3486.7 kW·h; the rated power of the supercapacitor is 13866.3 kW, and the rated capacity is 86.904 kW·h.

At present, the price of ESS is still high, but with the continuous development of related technologies and the evolution of market competition, the application of ESS will be more large-scale. The price used in this paper may deviate from the current energy storage market price, but the capacity configuration method proposed in this paper has a good reference value for the research of PPS configuration energy storage.

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