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Design and Optimization of Hybrid Energy Storage for Photovoltaicpower Fluctuation Smoothing Based on Frequency Analysis

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DESIGN AND OPTIMIZATION OF HYBRID ENERGY STORAGE FOR PHOTOVOLTAIC POWER FLUCTUATION SMOOTHING BASED ON FREQUENCY ANALYSIS

by

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ABSTRACT

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As the output power of photovoltaic generation system is affected by factors such as light intensity and temperature, it creates greater randomness and volatility. When the power changes quickly and fluctuates, the traditional energy storage devices often can't balance the power effectively. In this research Fast Fourier Transform (FFT) method is used to transform the photovoltaic stabilization power in the original time domain to the frequency domain for analysis. And percentage method was used to select the most typical PV data in the frequency domain. Then, the selected power was converted back to the time domain using Inverse Fast Fourier Transform (IFFT). Finally, A high-, medium-, and low-frequency hybrid energy storage system optimization model was established, and a particle optimization algorithm was used to obtain the most economical hybrid energy storage system configuration.

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Chapter 1 Introduction

In this chapter, the background, research status, research objective and article layout are presented.

1.1 Background

In recent years, the energy crisis has been a hot topic in various countries. The limited and pollution of petroleum and coal resources, and the difficulty of maintaining and damaging nuclear energy pose a threat to people. Scientists are striving to explore how to use natural resources such as wind, solar energy, and tidal energy. The effective use of these non-polluting natural resources, and their direct conversion to electrical energy can reduce the energy conversion pathways and increase the efficiency of energy use. These resources do not cause environmental pollution and are inexhaustible. Therefore, it is a trend to vigorously develop clean green energy [1].

1.1.1 Solar Power

Solar energy is a kind of renewable clean energy. Its advantages are inexhaustible and inexhaustible. Everyone can use it without considering monopolistic issues. It is a gift from nature [2]. Because of the scarcity and non-renewable energy such as oil, it will cause environmental problems. Under such circumstances, scientists in various countries have set off an upsurge of research on solar energy, promoted the progress of solar energy technology, and made unprecedented progress in the application of solar energy [1].

Solar energy is praised as green energy. Solar energy has the following characteristics [3]: Widely distributed. Simply put, there is solar energy wherever there is light. Solar energy is available everywhere on the surface of the Earth and no fuel is consumed; abundant reserves. There is no danger of depletion of solar energy, and solar energy can be used for 10 billion years; great energy. According to statistical analysis, the amount of energy that the sun puts on the earth in 40 seconds is equivalent to the sum of global energy consumption during the day; clean and environmentally friendly. No pollutant emissions, clean, no noise; energy is dispersed. The energy density of solar energy is very low, and it requires the use of a relatively large-scale energy harvesting device to meet actual needs; large randomness. Solar energy is greatly affected by weather conditions and day and night, so the energy reaching the ground is extremely unstable.

1.1.2 Energy Storage

Different energy storage have different characteristics in terms of functions, response times, and suitable storage duration, so it is possible to classify energy storage based on these characteristics[4][5][6]. In this research, ESS is divided into two classes of long-term ES and short-term ES.

(1) Long-term Energy Storage

ES with long response time is named Long-term ES. Long-term energy storage devices have the ability to supply or absorb electrical power for several hours. The long-term response energy storage devices have the ability to provide or take in electrical energy within several hours. Their power systems application is normally connected with energy management, frequency regulation or grid congestion management [7]. The use of long-term energy storage devices is expected to increase in the coming years due to the availability and variability of power generation as the integration of renewable energy sources in the energy system increases [8].

Electrochemical batteries are one of the most extensively used long-term ES. They use electrodes both as part of the electron transfer process and store the products or reactants through electrode solid-state reactions [7]. In terms of energy storage, there are many types of batteries being considered for use in energy storage. The main ones are:

- Nickel cadmium
- Lithium ion
- Sodium sulphur
- lead acid
- Sodium nickel chloride

(2) Short-term Energy Storage

In the transition period, such as line switching, load fluctuation and fault elimination, it is necessary to support the electrical power system that uses a short-term energy storage device. These applications prevent reliability and quality from collapsing the power system due to loss of synchronization or voltage instability.

Short-term response energy storage devices use is getting common in electrical systems with significant renewable energy penetration such as wind, biomass and weak interconnections, averting temporary defects and contributing to providing crucial system services such as instantaneous reserves and short-circuit capacity [9]. The main short-term energy storage devices and their operation are:

- Flywheels
- EDLC
- Magnetic Superconducting

In stand-alone photovoltaic systems, the energy storage device is circulated approximately once a day. At present, the cost of storage batteries is 30% to 35% of the independent photovoltaic systems, but they need to be replaced frequently; The number of charge and discharge cycles of a EDLC is more than 50,000 times, Its lifetime is comparable to that of battery packs, controllers and other devices [10], The use of EDLC energy storage optimizes system reliability, system installation costs and operating costs.

The EDLC is a physical energy storage device. Its charge and discharge process is essentially the process of adsorption and desorption of conductive ions on the electrode. Theoretically, the surface area of the electrode material is large so that its charging and discharging process are almost free from any limitation [11]. Therefore, its power density and charge-discharge efficiency are very high, and it is suitable for a renewable energy system with large input power fluctuations and high efficiency requirements [5]. Therefore, the photovoltaic system is very suitable for EDLC; it is very valuable in smoothing the load.

The high- and low-temperature characteristics of battery and other chemical power sources are far inferior to those of EDLC. EDLC has almost no special requirements for ambient temperature and is very suitable for working in photovoltaic system environments.

1.2 Research Status

In this section, we briefly present the research situation of ESS.

Literature [12] proposed the idea of hybrid energy storage with EDLC and batteries to optimize the lifetime of energy storage batteries. Theoretically proved that the hybrid energy storage can make full use of the complementary characteristics of the battery and the EDLC, improve the power output capability of the energy storage, reduce the number of charge and discharge of the battery and extend its service life; In the field of electric vehicles [13], construction machinery [14] and other fields, there are applications of hybrid energy storage. Literature [15, 16] studied the application of hybrid energy storage in distributed generation systems. The results show that the hybrid energy storage can optimize the charge and discharge process of the battery and reduce the number of charge and discharge cycles. Based on the above research, it can be foreseen that the hybrid energy storage of the EDLC and the battery has a good technical economy in responding to frequent and rapid power and energy changes of the micro grid.

At this stage, the research of hybrid energy storage systems for stabilizing the output power fluctuations of renewable energy sources only considers combinations of high and low frequency energy storage devices. The high frequency compensation frequency band fluctuation has the characteristics of large power density and small energy density. Using similar power type energy storage equipment can avoid excess energy and effectively reduce costs. The fluctuation of the low-frequency compensation frequency band has the characteristics of low power density and large energy density. Energy-type energy storage devices with similar characteristics can avoid excessive power capacity and effectively reduce costs. However, for the frequency fluctuation band between high frequency and low frequency, the existing literature divides it into high frequency or low frequency band for processing, which often leads to excessive capacity of the equipment and increases the system cost.

1.3 Research Objective and Article Layout

1.3.1 Research Objective

With the easier integration with ESS PV, there is great potential to take the place of wind in the next decade and become the most useful renewable energy. However, photovoltaic energy storage is volatile, not all photovoltaic energy can be immediately accepted by the grid, and the excess energy will be discarded by the grid. This part of energy is directly discarded without being used effectively, so how to store the photovoltaic energy beyond the grid needs is a key technical problem. Further, how to store energy efficiently and effectively, how to set the capacity of the energy storage battery and how to match the various types of batteries; That is, not all the energy produced by PV is stored and used because it is very costly; this research considers adapting to most of the energy storage needs, that is, not need meeting extreme weather conditions, while considering the reliability of energy storage.

In other words, in this research, a systematic strategy to design a great ESS solution to smooth fluctuations in PV production, taking into account the enormous change of PV output and the difference in cost between ESS types.

A common way of doing this was to build models of solar power plants using integrated ESS and observe how to use such storage systems to reduce the variability in plant production.

A valid way of doing this was to build a photovoltaic plant model with kinds of ESS and experiment how to configurate such a storage system to cut down the variability of the plant output. Besides, this research carry out experiments using various configurations of the ESS model to find the desired output characteristics according to the specific user-defined system objectives, such as leveling the output of the system to ensure that the power system can fluctuate within the normal range, which can meet 80% of the weather pattern, that is photovoltaic power can be accepted by the grid in 80% of cases. Then analyzed the outcomes of these tests and reviewed the scheme of the anticipated utility of the solar system with storages.

In this research, one FFT based approach was put forward, which can effectively calculate the full spectra of individual components with different frequencies that cause PV output fluctuations. The fluctuation of the photovoltaic output is calculated using the annual PV data measured at experimental station in Milwaukee for 32 days. A systematic approach is used to match the storage devices at different charging and discharging rates in market, to use the FFT results and determine the most effective ESS solution at the lowest cost.

A systematic approach is studied using frequency domain results and coordinating with available storage devices with different charging and discharging rates in order to choose the most effective ESS solution with lowest cost. The key idea in the proposal is to on the premise of maintaining certain reliability, improve the economic efficiency of PV energy storage configuration. Use FFT to calculate in the frequency domain and optimize the energy data that needs to be stored. Then, the entire spectrum of undesired PV output changes is divided into different parts. Every part uses the ESS of the corresponding frequency band. By dividing the entire spectrum and optimizing the algorithm, the minimum cost is achieved.

1.3.2 Article Layout

The thesis is organized in the following chapters:

Chapter 1 presents the composition of the photovoltaic energy generation technology, the architecture of the system, the energy storage system, and recent research in the area. Research objectives and an article layout are also presented in this chapter.

Chapter 2 will discuss the defects in previous papers. Introduces the FFT method used in this article and the advantages of this method, It will introduce the concept and calculate the balance power, while calculating algorithm to figure out the grid acceptable power. All calculations above are important for the following research.

Chapter 3 selects this study case, explains how to count PV output power so that it can cover a certain percentage of weather conditions in the FFT method. Changing cutoff points locations and concluding cycle life and loss, will help calculate low, medium and high frequency power and energy using the FFT method

Chapter 4 introduces Particle Swarm Optimization (PSO)，then design ESS with the least cost and the highest reliability. Take an 80% example and compare with 70%, 90%, 100% and average values. The comparison includes cutoff points, change time, and cost. Analyze the economic advantages and reliability of the percentage method.

Chapter 5 is composed of the verification of this design.

Chapter 6 presents the conclusion and prospects the future work.

Chapter 2 Data processing

2.1 FFT Method

It is not easy to select typical PV data directly in the time domain. This paper uses the FFT method to process PV data in the frequency domain to analyze the weather pattern more deeply and improve cost effective.

2.1.1 Classic Fourier Transform

$$F(\omega)=\int_{-\infty}^{+\infty} f(t)e^{-j\omega t}dt \tag{2.1}$$

$$f(t)=\frac{1}{2\pi}\int_{-\infty}^{+\infty} F(\omega)e^{j\omega t}dt \tag{2.2}$$

Among them, formula (2.1) is called Fourier transform, formula (2.2) is called inverse Fourier transform. It is worth noting that the traditional Fourier transform requirements represent the original signal that should satisfy the Dirichli condition. In practical engineering, basically all signals meet the Dirichli condition.

In equation (2.1), in fact, we use $F(\omega)$ to make a spectrum analysis of the original signal $f(t)$. Because for a fixed frequency, its value is:

$$F(\mathrm{a})=\int_{-\infty}^{+\infty} f(t)e^{-jat}dt \tag{2.3}$$

Equation (2.3) gives the frequency of $F(\omega)$ at $\omega=a$. We can completely understand the size of frequency component $f(t)$ contained in the original signal as $F(\omega)$. Therefore, we can easily analyze the non-periodic $f(t)$ signal through the Fourier transform so that different frequency components can be analyzed [17].

2.1.2 Discrete Fourier Transform

$$X(k)=\sum_{k=0}^{N-1}x(n)e^{-j\frac{2\pi}{N}kn} \tag{2.4}$$

Equation (2.4) is the discrete Fourier transform [18], and

$$x(n)=\frac{1}{N}\sum_{k=0}^{N-1}X(K)\mathrm{e}^{i\frac{2\pi}{N}kn} \tag{2.5}$$

Then the formula (2.5) is called discrete Fourier inverse transform. It can be seen from the formula (2.4) and (2.5) that $X(K)$ represents the discretization of the frequency domain, and the period N. $x(n)$ represents the discretization of the time domain, and the period is also N.

2.1.3 Fast Fourier Transform

Finding an N-point signal requires n^2 complex multiplications and $N(N-1)$ complex additions. If N is large, the DFT has a large amount of computation and takes a long time. In order to solve this problem, fast Fourier transform (FFT) is generally used in practical applications to implement fast calculation of DFT.

Since the calculation of FFT is significantly reduced compared to other Fourier algorithms, FFT has been widely used in real-time processing of signals including the synthesis of speech signals, the tracking resolution of sonar and radar signals, and the digitalization and multiplex conversion of communication signals. The emergence of FFT algorithms has played an important role in the development of related disciplines in digital signal processing [18].

2.1.4 Time-Frequency Conversion of Photovoltaic Power Using FFT

For photovoltaic power signals that need to be suppressed, the FFT can realize the function of analyzing signals from the frequency domain, which facilitates more intuitive and clear analysis of the spectral characteristics of balanced power, and directly performs filtering operation in the frequency domain, which is different from the traditional filter [19]. Domain analysis filtering has almost no errors and results are more accurate. In this paper, FFT is used to perform the time-to-frequency conversion of the PV balance power signal to obtain the balance power amplitude and frequency characteristics:

$$P_b(k) = FFT[P_b(n)] = \sum_{n=0}^{M-1} P_b(n) e^{-j(2\pi/M)kn}, k = 0,1...,M-1 \tag{2.6}$$

After decomposing, get the signal's amplitude result S_b and frequency result f_b:

$$\begin{cases} S_b = FFT(P_b) = [S_b(1),...,S_b(n),...,S_b(N_S)]^T \\ f_b = [f_b(1),...f_b(n),...f_b(N_S)]^T \end{cases} \tag{2.7}$$

In the formula: N_s Indicates total sample data; $S_b=R_b(n)+jI_b(n)$ Denotes the amplitude corresponding to the nth frequency in the FFT transform result; $R_b(n)$、$I_b(n)$ corresponds to the real and imaginary parts of the amplitude, respectively; f_b denotes the frequency column vector corresponding to S_b:

$$f_b(n)=\frac{(n-1)\cdot f_S}{N_S}=\frac{n-1}{T_S\cdot N_S} \quad (2.8)$$

In the formula：f Indicates the sampling frequency of the sample data (unit: Hz), T_S indicates the sampling period of the sample data (unit: s).

2.2 Grid Acceptable Power

All kinds of energy access systems can cause instability to the photovoltaic system, which requires balancing energy to absorb and supplement energy [20]. It is hard to predict solar power advance and will cause a series of problems including the reliability of the system [21].

Acceptable means the ability of the system to maintain a stable operation in case of emergency or load change. The power of the ESS is related to the power grid's ability to accept fluctuations in electrical energy.

In this research, all data comes from a small PV station. According to the limit value of power fluctuation as shown in Table 2-1, the maximum power fluctuations, which the grid can accept, is 0.2MW per minute [22].

Table 2-1 Maximum power variation limit in PV station

PV station type	Maximum power variation in 10min/MW	Maximum power variation in 1min/MW
Small	Installed capacity	0.2
Medium	Installed capacity	Installed capacity/5
Large	Installed capacity	Installed capacity/10

Since 0.2MW is the maximum fluctuation value for 1 minute, in this research, the sampling interval is one second. To meet the standard of 0.2MW per minute, we set a one-second power fluctuation to be 1/60 of a minute fluctuation, which is about 3kW. So the Grid allowable power can be calculated using PV data with the above rules. As shown in Figure 2-1, the power fluctuation per second cannot be greater than ±3kw. If it is greater than ±3kw, the PV output of the next second is equal to ±3kw in the last second, which indicated by the yellow box. In this case it is ± 3 kW. The original PV output is represented by the green line, and power fluctuations that are actually acceptable in the power grid are represented by a chalk line.

With the input of photovoltaic output data, the permitted network power can be obtained as shown in Figure 2-1. If the next second of photovoltaic data exceeds this range, the algorithm will automatically correct (as shown in time interval1, 2, 3, 6 and

7). If the energy fluctuations don't go beyond this range keep the original value (as shown in time interval 4, and 5).

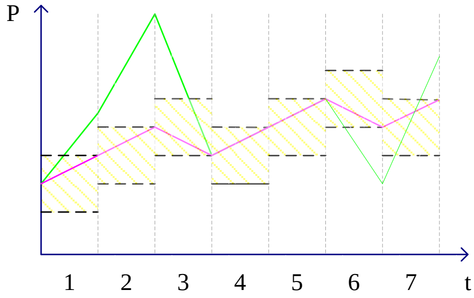


Figure 2-1 grid Acceptable Power

2.3 Balancing Power

The ESS is applied to maintain the balance between the photovoltaic output power and the power input of the network to meet the allowable power grid levels. In order to achieve this goal, the concept of system balance is developed and is widely used in all systems. According to reference [23], balancing represents the energy of excess or shortage; in photovoltaics, that is to say, the fluctuations are large enough not to be accepted or run short by the grid. Power balance is an important element of the size of ES capability.

Based on PV output power P_o, grid acceptable power P_a, the balancing power P_b can be expressed as follows:

$$P_b = P_o - P_a \tag{2.9}$$

Where:

P_b>0: The PV generates extra power need to be absorbed by ESS. *ES* is being charged when P_b>0.

P_b<0: The PV creates insufficient available power that ESS needs to provide. E*S* is being discharged when P_b<0.

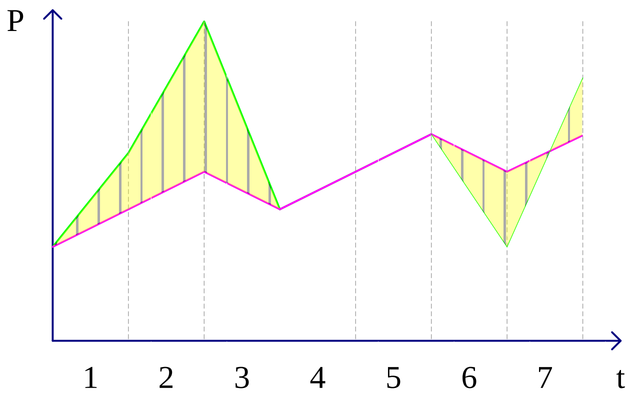


Figure 2-2 power balance

The power balance shown in Figure 2-2 is the selected solar energy power required to be absorbed by the ESS during the operation of the photovoltaic system.

2.4 Previous research and progress in this article

The previous paper [24] discussed the most typical PV storage price, but only used one day of PV data. The data is not typical and did not consider eliminating the most extreme weather conditions. The previous paper [25] discussed the 80% comparison of peak, peak, and average, but did not choose the best case and did not calculate the corresponding price. Based on the former, this paper will analyze long-term data, eliminate extreme weather conditions, and consider various data processing methods to determine the most typical statistical data processing method.

2.5 Energy Capacity Considering State of Charge

Represents the ratio of the remaining capacity of the battery after it has been used for a period of time or is left unused for a long period of time. Its value ranges from 0 to 1. When SOC =0, the battery is fully discharged. When SOC =1, the battery is fully charged [26].

Taking SOC factor into consideration, In order to ensure that the energy stored by the ESS can always meet the demand of the power grid, regardless of whether it discharges or charges, the system is considered to return to 50% SOC every morning at 6:10am after all night control adjustment [24].

Thus the energy capacity of each battery should be 2 times of the calculated energy capacity.

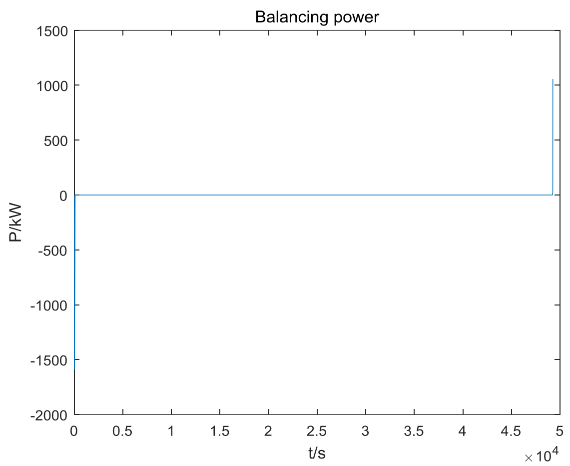
Chapter 3 Cost Optimization

Based on spectrum analysis, this chapter proposes using high, medium and low-frequency of hybrid energy storage systems to suppress the output power fluctuations of photovoltaic power generation systems. This chapter analyzes the balanced power of the photovoltaic system from the frequency domain through FFT transformation, and combines the response characteristics of the energy storage devices in each frequency band to divide the operating frequency range of the three types of energy storage devices. And for each frequency band, the capacity of energy storage equipment is configured, taking the rated capacity of the energy storage device according to the aforementioned parameters and the SOC and other factors, then the calculation results are revised.

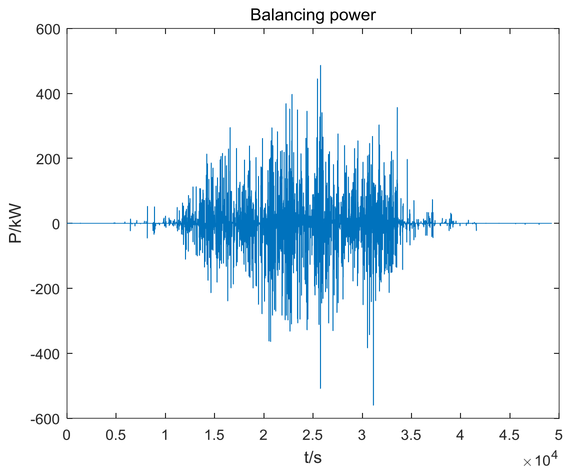
This section selects the best from the three cases (average value, peck value and percentage value) for subsequent experiments. It explains how to count PV output power so that it can cover a certain percentage of weather conditions. It introduces ESS types, also covers ESS energy and energy capacity calculations at different cutting points according to the sizing method.

3.1 Case choose

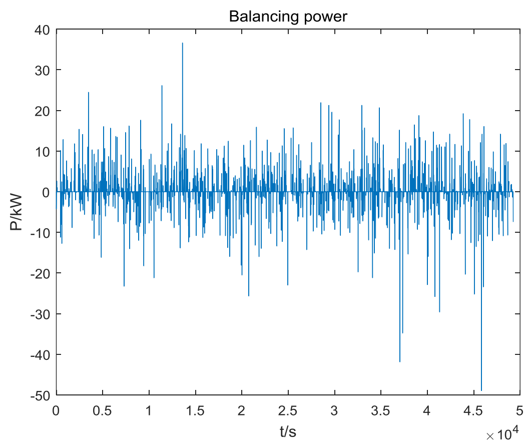
Based on 32 days' data which is recorded every seconds (sampling frequency: 1Hz and 49260 data per day) between 6:10 a.m. and 19:50 p.m. in 2015, Milwaukee. The weather in 32 days can be sorted and analyzed in 3 types: average value, peck value and percentage value. That is to say, the data is converted to the frequency domain by FFT, and statistic the average value, peck value and percentage value. In frequency domain, the average value is obtained by averaging the plural forms of all the data at each frequency point; Peck value is the complex number with the largest absolute value of all data at each frequency point; percentage value is obtained by sorting the data of each frequency point and the data in the same ordinal number is counted. The typical mode performs IFFT conversion to the time domain, and then configures the storage battery. Three modes of photovoltaic power fluctuation curve are shown in Figure 3-1, all of the above mentioned figures are based on the Angle orientation method which will mention in the next section.



(a) Balance power of average pattern



(*b*) Balance power of peak pattern



(*c*) Balance power of percentage method

Figure 3-1 balance power of three case

It can be seen from these curves that photovoltaic power has the largest fluctuation in peck value. That's because the data selected at each frequency in the frequency domain is the most extreme, so power fluctuation itself is stronger than average value and percentage value. It is worth noting that this model is not real, but is based on the statistics of existing data.

Although the configuration of the energy storage battery according to the extreme conditions can ensure that all the photovoltaics are not wasted and stored, the photovoltaic energy generation with high energy storage requirements is extremely rare. To meet all the photovoltaic power generation conditions, the battery configuration requirements are high and it will increase the economic costs； However, according to the average energy storage configuration, the energy required to be stabilized by the energy storage battery is almost zero, and it does not function to store excess energy. Therefore, this research studies the photovoltaic energy storage to meet part of the energy storage requirements, sort the photovoltaic data in the frequency domain, select a certain percentage of photovoltaic power generation, and configure the photovoltaic energy storage, so that it can meet most of the photovoltaic energy storage needs and can also meet economic requirements.

All of the following are studies of percentage method.

3.2 The data processing of PV output power

Compared with choosing the peak, choosing to meet a certain percentage of the weather conditions, the more economical and more typical, more representative of the most frequent occurrence. Because all the photovoltaic data after Fourier transform, the frequency domain data has a few particularly big value, these data are not typical. Increase the capacity of the battery storage to store these rare photovoltaic (PV) power is not economical. Take 87% and 100% as examples, balance power in frequency domain shown in Figure 3-2. By comparing 87% and 100%, it can be seen that 87% is less than 100% power fluctuation, and the absolute value of power is also smaller, which shows 87% will make effective use of energy storage equipment.

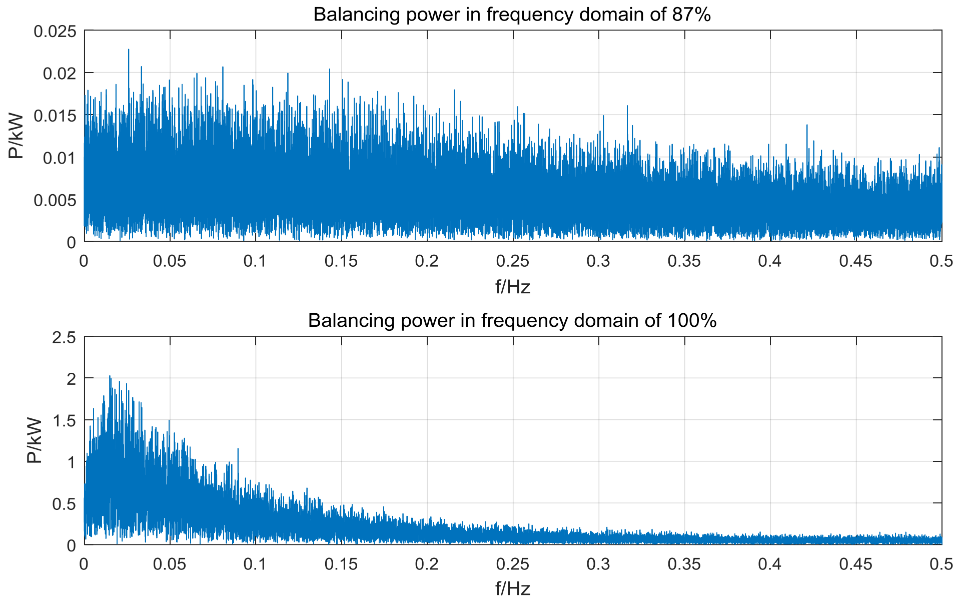


Figure 3-2 Comparison of 87% and 100% balance power

So this article use percentages method for data processing as follows: the size, a total of X days, every day there are Y frequency domain data The data of the same order is selected after the power data of the same frequency is arranged in absolute value. In my research, daily data is converted to frequency domain using FFT method; a total of 32 days of data, so there are 32 data at each frequency point. The data of each frequency domain is ranked from the largest to the smallest, and 80% of all the data, that is, the 27-th data. Take 0.1 Hz as an example, there are a total of 32 frequency data:

0.0258	0.0619	0.0662	0.0662	0.0802	0.0838	0.0910	0.1379

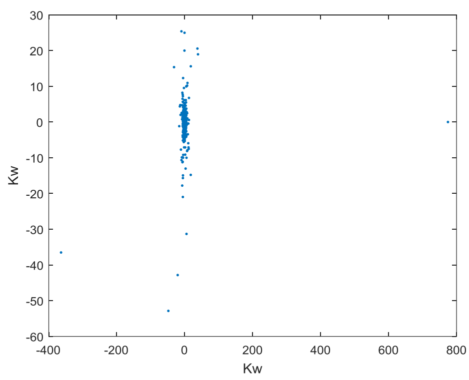
0.1422	0.1775	0.1811	0.1858	0.2819	0.3396	0.3451	0.3908
0.4687	0.5796	0.8316	0.8554	0.8885	0.8898	1.5560	1.5560
1.6945	1.8129	**1.8439**	1.9210	2.3970	3.0343	3.3438	3.7730

The 27th bit is 1.8439.And at 0.11 Hz, there are a total of 32 frequency data:

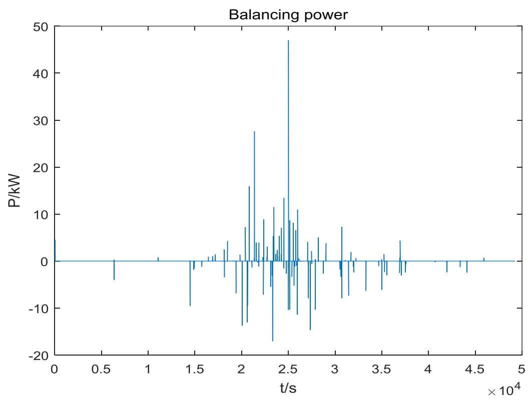
0.0505	0.0647	0.0688	0.0781	0.0999	0.1234	0.1642	0.1642
0.1913	0.2192	0.2650	0.4338	0.4792	0.4865	0.5687	0.5763
0.5813	0.5950	0.6326	0.6506	1.1897	1.3303	1.4767	1.6142
1.6789	1.6789	**1.8099**	1.8574	1.9572	2.2558	2.7686	2.8893

The 27th bit is 1.8099; combining 80% of all frequency domain data is new frequency domain data.

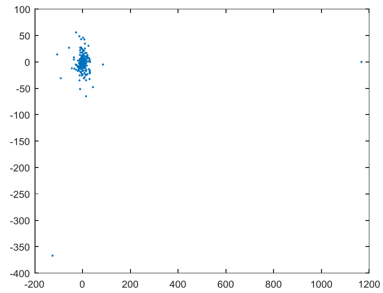
Angle aspect, there are two ways, the first way to choose peak corresponding angle, the angle is multiplied by the absolute value to get the new data, 80% as an example is shown in Figure 3-3(*a*) and (*b*), the second way is to have the sorted data and the previous data orientation. The angle is multiplied by the absolute value to get the new data, 80% as an example is shown in Figure 3-3(*c*) and (*d*). (*a*) Compared with the (*c*), the phases of (*a*) are scattered, because only take the angle corresponding to 80% point, and no other angle is involved. The vector of the (*c*) is a vector sum of 0%~80% of the data at each frequency point, the influence of each frequency point is integrated. The reason why the vector sum is considered and the average of all the vectors is not taken into consideration is that the average will make the positive and negative of these angles be integrated, thus failing to meet the requirement of 80%; the power distribution of the (*b*) is more uniform than that of the (*d*), and the distribution of (*d*) is more extreme, again illustrating that phase summation is more effective. According to the method of this article, the power data of each frequency has a value that satisfies a certain percentage. The combination of these values in the time domain is a typical day. After the inverse Fourier transform, the time domain data is not the actual data, and each time data is the typical and satisfying economic requirement.



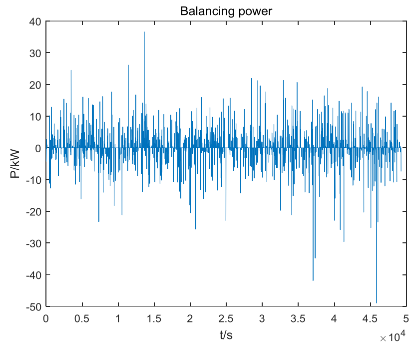
(*a*) Amplitude and orientation's angle in the frequency domain



(*b*) Balance power of absolute value with peak's angle



(*c*) Amplitude and orientation's angle in the frequency domain



(*d*) Balance power of absolute value with orientation's angle

Figure 3-3 Frequency domain components and balance power after percentage method processing

3.3 Cutoff points and ESS types

3.3.1 ESS types

According to the data based on the response time of each battery, three types of ESS, lead storage battery, lithium ion battery and EDLC are studied according to literature [27], [28] and [29].

Table 3-1 ESS type

ESS	Type	Shortest response time	Maximum response frequency
Lead acid battery	long-term	2min	8.33×10^{-3}Hz
lithium ion battery	long-term	1min	0.0167Hz

EDLC	short-term	1s	1.00Hz

Based on Nyquist–Shannon sampling theorem, Sampling is the conversion of a signal (that is, a continuous function of time or space) into a sequence of values (that is, discrete functions in time or space). Shannon's version of the theorem states [30]:

If the function x (t) does not contain frequencies above B Hertz, it is completely determined by specifying the vertical axis in a series of points separated by 1/(2B) seconds. In another words, signal function *x*(*t*) must contain no sinusoidal component at exactly frequency B, or that B must be strictly less than ½ the sample rate. Since the sampling frequency in this study is 1 sample/second, the Nyquist frequency is 0.5 Hz. Which means, The working frequency range of all batteries together should cover [0,0.5] Hz. Frequency range lead-acid, lithium and EDLC is shown in Figure 3-2.

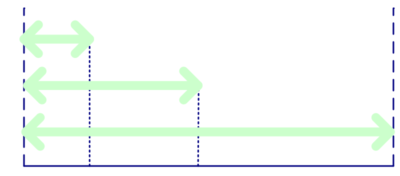


Figure 3-4 Frequency band each ESS can cover

For the purpose of this research hybrid energy storage, need lead acid, lithium and EDLC three battery, as shown in Figure 3-4 lead acid and lithium can only be used for low frequency energy storage, and EDLC can cover the high frequency part or even all frequency range; But the cost of using an EDLC single-type battery is higher than the cost of the hybrid energy storage.

3.3.2 Cutoff points

The balance power fluctuations that need to be balanced are further subdivided into high, medium, and low frequency bands, and energy storage devices that are commonly used in photovoltaic energy storage systems with the fastest, medium, and slowest response speeds are used: EDLC lead acid and lithium. lithium battery, Among them, the lithium battery dynamic response is slow, the lowest per unit of energy costs, suitable for low-frequency fluctuations in energy density; lead-acid battery response speed and cost is relatively compromise, suitable for medium-frequency fluctuations; EDLC response speed, long cycle life, power Low cost, suitable for high frequency fluctuations in power density.

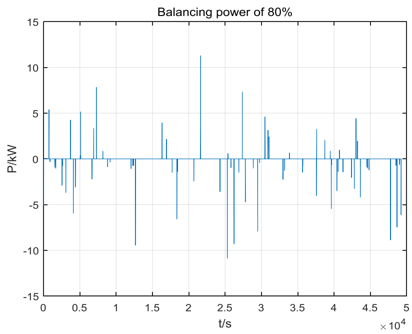
In addition, the cutoff points for the three batteries should meet the following conditions: cut off points for low and mid frequencies are lower than cutoff points for mid and high frequencies.

3.4 Capacity and its revision

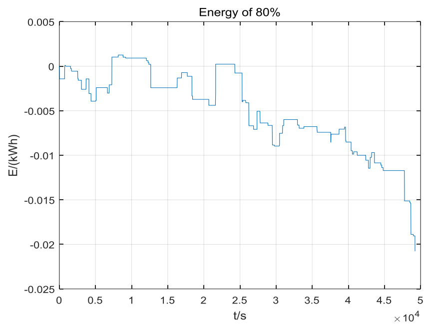
3.4.1 ESS Power and Energy Capacity

Because the real-time power within different frequency ranges accumulate or offset each other, the total power capacity is not practically important. However, Capacity is an important measure of the price per unit of ES.

As shown in Figure 3-5, the total energy curve is calculated by integrating the balance power.



(*a*) Balance power of 80%



(*b*) Energy of 80%

Figure 3-5 Balance power and energy of 80%

Once the energy capacities of each ES are determined, it is necessary to confirm that the total value is greater than or equal to the minimum required total energy capacity after adding them together. In other words, if you're thinking about long-term, medium, and short-term energy ES together, then the total capacity of any ES in the system should not be less than the energy capacity.

3.4.2 Capacity revision

Due to the fact that the battery power and power capacity provided by the actual manufacturer are certain, it will hardly match the two capacities required exactly. In order to solve the above problems, when selecting the equipment type, it is necessary to revise the calculated energy storage capacity or calculated energy capacity according to the actual capacity parameter of the storage equipment, to ensure that the rated power and rated energy requirements of the actual energy storage equipment are met. So according to the revised energy storage capacity, the project selection and configuration can be directly carried out.

For the actual energy storage device in the market, the total cost of the energy storage device can be calculated by both energy cost and power cost. The cost can be calculated as (3-1),

$$c_E \cdot E_{rated} = c_P \cdot P_{rated} \tag{3-1}$$

In the formula: rated energy c_E, rated power c_P, unit energy cost E_{rated} and unit power cost P_{rated}.

If $c_E \cdot E_{rated} > c_P \cdot P_{rated}$, take the minimum calculated energy capacity as the configuration selection standard, and revise the energy storage capacity E_{ES} for energy storage:

$$P_{ES \cdot rated} = \frac{E_{ES}}{k} \tag{3-2}$$

Similarly, if $c_E{\cdot}E_{rated}<c_P{\cdot}P_{rated}$, the minimum calculated power capacity is the configuration selection standard, and the energy storage P_{ES} needs to be revised.

$$E_{ES}=k\cdot P_{ES\cdot rated} \tag{3-3}$$

3.5 Hybrid energy storage system cost optimization

When the hybrid energy storage system satisfies the calculated and revised power capacity and energy capacity, in order to make the planning more reasonable, the actual impact of the project should also be considered, such as capacity loss and cycle life during the charging process of the energy storage equipment. The system cost calculated in this way is closer to reality. This section will describe in detail the cost calculation method of the hybrid energy storage system considering the capacity loss and cycle life, and the configuration optimization method based on the lowest cost hybrid energy storage system.

The size of the energy storage equipment and the amount of energy storage required within the operating life of the PV power plant are directly related to the frequency of division of the compensation frequency band. According to the spectrum analysis, with the change of the frequency of the high and low frequency cutoff points, the width of each compensation frequency band changes accordingly. The capacity of the corresponding energy storage equipment will also change, and at the same time affect the required number of energy storage devices. The total system cost will also be affected. The design of the corresponding hybrid energy storage system should meet the requirements of power fluctuation stabilization, and strive to achieve the lowest total system cost. This section will consider the life cycle of energy storage equipment and optimize the cost of the hybrid system by finding the optimal segmentation frequency that meets the lowest system cost.

3.5.1 Capacity loss

Capacity loss is a phenomenon in which the amount of electricity that the battery can provide during repetitive charging is gradually reduced at the rated voltage [31].

The battery will lose storage capacity after each charge and discharge, and its capacity for charge and discharge will decrease. The total energy that an ESS can provide during all charge and discharge processes can be determined by equation (3-5).

$$\begin{aligned}&\textit{total ESD energy output after number of cycles } n\\&=\frac{1}{2}E(3kWh)\times\{1 + (1-m) + (1-2m) + \cdots + [1-(n-1)m]\}\end{aligned} \tag{3-4}$$

In this formula: m is equal to the percentage of average capacity loss per cycle of ESS, n represents number of battery cycles.

In this research, we assume that the capacity loss of a battery cannot exceed 40%

[32]. Using data from Table3-2, the average capacity loss of several batteries used in this research can be calculated according to the equation (3-4).

Table 3-2 Parameter of ESS

Energy storage type	Cost/ per unit		Cycle life/times	Limitation of SOC
	C_P (\$ / kW)	C_E (\$ / kWh)		
Lead-acid battery	300	200	1000	0.15-0.85
Lithium battery	1000	300	2500	0.15-0.85
EDLC	300	2000	100000	0.05-0.95

Lead-acid battery: 4×10^{-2} %

Lithium-ion battery: 2×10^{-2} %

EDLC: 4×10^{-4} %

3.5.2 Cycle life

The cycle life of energy storage equipment usually refers to the number of times before the battery fails to fully charge and discharge [7]. The design and operation period of the photovoltaic test power station sampled in this research is 15 years. During the operation period, ESS usually require several replacements. So, this research considers cycle life of energy storage equipment to calculate the total number of ESS required within the operating time. Following is the formula used to calculate the total number of energy storage devices required during the operating year:

$$N_r = ceil\left(\frac{E_{station\text{-}total}}{E_{ES\text{-}total}}\right) \tag{3-5}$$

In (3-5)：N_r, the total number of energy storage equipment; ceil indicates that the calculation result is rounded up; $E_{ES\text{-}total}$, all energy stored in or discharged by a unit's energy storage device; $E_{station\text{-}total}$, it is the total energy required to compensate or absorb during the operation period of the photovoltaic power plant.

The $E_{ES\text{-}total}$ can be obtained by multiplying the revised energy storage capacity by the number of cycles N_c, consider SOC taking 0.5 of the spare energy:

$$E_{ES\text{-}total} = \frac{E_{ES\text{-}revised} \cdot N_c}{2} \tag{3-6}$$

$E_{station\text{-}total}$ can obtained according the maximum total energy can be compensated or consumed in a single day multiplied by the working days of the plant:

$$E_{station\text{-}total} = 15 \times 365 \times E_{station\text{-}oneday(max)} \tag{3-7}$$

Total energy $E_{station\text{-}oneday}$ take the data processed with the percentage method. The power fluctuations are positive $P_{b\text{-}positive}$ and negative $P_{b\text{-}negative}$, and selecting the larger absolute value of positive and negative integrals as the total energy at that day：

$$E_{station\text{-}oneday} = \max\left(\int P_{b-positive}dt, \left|\int P_{b-negative}dt\right|\right) \tag{3-8}$$

Chapter 4 Algorithms and comparisons

In this chapter, considering the cycle life of energy storage equipment comprehensively and aiming at the lowest total cost of the hybrid energy storage system, an optimization model of high, medium and low frequency hybrid energy storage systems is established and solved using a Particle Swarm Optimization. These cutoff points are adjusted to design ESS with the least cost and the highest reliability. Finally calculate the cost and change time of high, medium and low frequency batteries using 80% as an example.

Finally, the system cost, stabilization effect, and actual utilization of energy storage capacity of the hybrid energy storage combination under the same stabilization target are investigated and compared.

4.1 Consideration of economical hybrid energy storage system

4.1.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an intelligent computing algorithm in addition to ant colony algorithm and fish school algorithm.

The PSO algorithm is inspired by this biological population behavior and used to solve the optimization problem. Each particle in the algorithm represents a potential solution to the problem. Each particle corresponds to a fitness value determined by the fitness function. The velocity of the particle determines the direction and distance of the particle's movement. The velocity is dynamically adjusted with the experience of the movement of itself and other particles, thereby realizing the individual's optimization in the solvable space. PSO flowchart are shown in Figure 4-1.

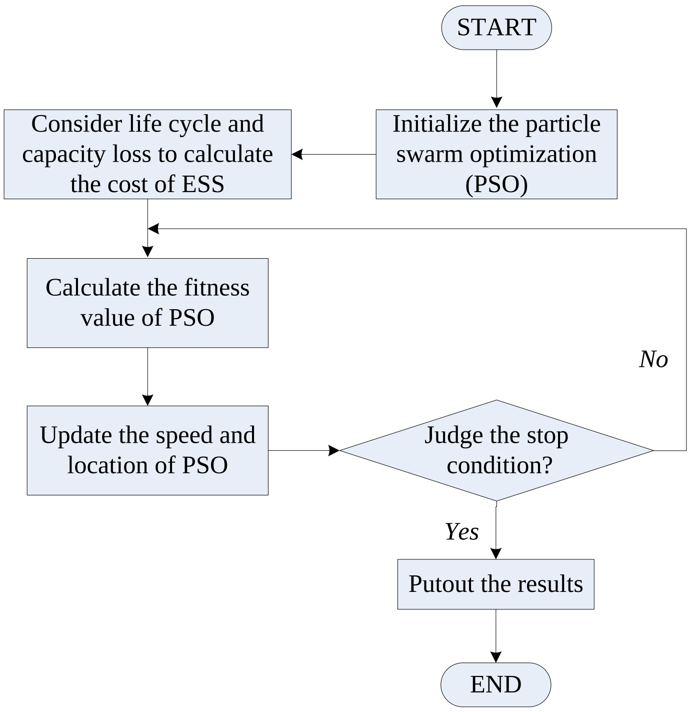


Figure 4-1 PSO flowchart

4.1.2 Optimization model

Assume that in a D-dimensional search space, a population consisting of n particles $\boldsymbol{X}=[\boldsymbol{X}_1,\boldsymbol{X}_2,\cdots,\boldsymbol{X}_n]$. The *i-th* particle in the population is represented by a D-dimensional vector $\boldsymbol{X}_i=[x_{i1},x_{i2},\cdots,x_{iD}]^T$, which represents the position of the *i*-th particle in the D-dimensional search space and also represents a potential solution to the problem. At present, the velocity of the i-th particle is $\boldsymbol{V_i}=[v_{i1},v_{i2},\cdots,v_{iD}]^T$, and its individual extreme value can be expressed as $\boldsymbol{P_i}=[p_{i1},p_{i2}, \cdots,p_{iD}]^T$, The global extreme value of the population is $\boldsymbol{P_g}=[p_{g1},p_{g2}, \cdots,p_{gD}]^T$. After going through k iterations, update the particle's velocity and position. The formula is as follows:

$$v_{id}^{k+1} = w \cdot v_{id}^{k} + c_1 \cdot r_1 \cdot (p_{id}^{k} - x_{id}^{k}) + c_2 \cdot r_2 \cdot (p_{gd}^{k} - x_{id}^{k}) \tag{4-1}$$

$$x_{id}^{k+1} = x_{id}^{k} + v_{id}^{k+1} \tag{4-2}$$

Where: w is the inertia weight, its role is to control the impact of the speed of the previous iteration on the current speed; $d=1,2,\cdots,D$; $i=1,2,\cdots,n$; c_1 and c_2 represent acceleration factors, r1 and r2 represent random numbers distributed between [0,1]; By setting the particle velocity interval $[v_{\min},v_{\max}]$ and the position interval $[x_{\min},x_{\max}]$, the particle's search behavior is constrained to prevent blind search of particles.

The choice of the inertia weight coefficient w plays an important role in the convergence performance of the PSO algorithm. In theory, the value of w in the initial iteration of PSO algorithm should be as large as possible to ensure a good global search capability of the PSO algorithm. With the increase of the number of iterations, that is, the algorithm requires a strong local search capability at the later stages of the iteration to ensure that the algorithm can converge. In this case, the value of w should be as small as possible. It can be seen that the value of the inertia weight coefficient w should be a process that increases from large to small as the number of iterations increases. Therefore, this chapter changes the w-value of the particle swarm algorithm as follows:

$$w = w_{end} + (w_{start} - w_{end}) \times \tan(0.785 \times (1 - (\frac{k}{T_{\max}})^{\lambda})) \tag{4-3}$$

Where: w_{start} represents the initial value of the inertia weight, it is also the maximum; w_{end} represents the inertia weight at the end of the iteration, which is also the minimum value; k represents the current number of iterations; λ represents the control factor, controlling the change of w.

4.1.3 Establish the optimization model

In this section, a particle swarm optimization (PSO) algorithm is proposed to develop the optimal configuration model of the equipment capacity in hybrid energy storage system to stabilize the PV output power surge. Let the maximum compensation frequency of the three types of energy storage equipment, which are lead acid battery, lithium battery and EDLC, as the decision variables. Considering the economic cost, SOC limit, cycle life and other factors of the three types of energy storage equipment, we take the lowest total cost of the energy storage system as the objective to optimize the solution.

(1) Decision variables

Because the size of the cutoff frequency directly determines the size of each energy storage device, thus affecting the total cost of the hybrid energy storage system. In the optimization model of the hybrid energy storage system considering the economy, since the super capacitor completes the energy storage operation at [0, 1] Hz, no special treatment is performed. Taking the highest cutoff frequency of lead-acid batteries and lithium batteries as a decision variable, separately denoted f_N and f_Q. The final tri-band division result is: lead acid battery frequency is [0, f_N]Hz; Lithium battery frequency is [f_N, f_Q]Hz; EDLC is [f_Q, 1]Hz。

(2) Objective function

The goal of the optimization design in this paper is to obtain the maximum economic benefit under the condition of meeting the system requirements. The relevant parameters of the energy storage equipment in the tri-band hybrid energy storage system and the calculation method of the corresponding system cost have been elaborated in Chapter 3, so the objective function can be expressed as:

$$\begin{aligned} \min c = & E_{ES-revised-low} \cdot c_{E\text{-}low} \cdot N_{r-low} \\ & + E_{ES-revised-mid} \cdot c_{E\text{-mid}} \cdot N_{r-mid} \\ & + E_{ES-revised-high} \cdot c_{E\text{-high}} \cdot N_{r-high} \end{aligned} \tag{4-4}$$

(3) Restrictions

Each decision variable can be continuously taken within the initial response frequency range. The specific expression is：

$$\begin{cases} f_N^{\min} \le f_N \le f_N^{\max} \\ f_Q^{\min} \le f_Q \le f_Q^{\max} \\ f_N < f_Q \end{cases} \tag{4-5}$$

In the formula: $f_N^{\min}$, $f_N^{\max}$, they are the lower and upper limits of the sodium-sulfur battery cutoff point; $f_Q^{\min}$, $f_Q^{\max}$, they are the lower and upper limits of the lead-acid battery cutoff point.

4.2 Examples Analysis

4.2.1 Energy storage model establishment and optimization solution

Taking the lead-acid battery, lithium battery and super capacitor studied in this research as an example, a high-, medium-, and low-frequency hybrid energy storage equipment optimization model based on particle optimization algorithm is established.

(1) Decision variables: f_N and f_Q。

(2) Objective function: same with (4-4)。

Since the objective function is the lowest total system economic cost in this example, the function is non-negative, so the objective function value can be directly used as the individual's fitness.

(3) Restrictions:

$$\begin{cases} f_N^{\min} \le f_N \le f_N^{\max} \\ f_Q^{\min} \le f_Q \le f_Q^{\max} \\ f_N < f_Q \end{cases} \tag{4-6}$$

The above equation represents the highest cutoff point for lead-acid batteries, lithium batteries, and super-capacitors when the economic efficiency is satisfied, and the power capacity, energy capacity, and required amount of the energy storage equipment under each cutoff points can be obtained.

PSO algorithm parameter settings are as follows： set the group size to M=40， the maximum number of iterations $T_{\max}$=20，maximum inertia weight w_{start}=0.9，minimum inertia weight w_{end}=0.4， control factor λ=0.6， acceleration factor c_1=c_2=1.49445。

To facilitate analysis and comparison, the highest cutoff point of each compensation device obtained by the solution is converted into the cutoff frequency between devices: The highest cutoff frequency of lead-acid batteries is the high-frequency cutoff points of the ESS system; the highest cutoff frequency of the sodium-sulfur battery is the low-frequency cutoff points of the ESS system.

4.2.2 Energy storage model establishment and optimization solution

The third chapter already selected the energy storage modeling by percentage method, this section will calculate the specific goal with 80%.

Since the PV output power is mainly affected by changes in temperature and light intensity, the temperature of the photovoltaic test station studied in this paper is controlled at a constant temperature of 25 ℃, and its output power and light intensity are approximately linear because the light intensity in the Milwaukee, Wisconsin region is mainly affected by the weather. In order to select more general data, a total of 32 days of PV data from March, July, September and November, 2015 were selected for statistics. Since photovoltaics do not produce electricity at night, daily data of 6:40 a.m.-

7:10 p.m. were selected for analysis. Considering the effect of fluctuating power and the economic cost of the energy storage system, the photovoltaic output power that can meet 80% of the weather conditions in the frequency domain is selected as the design standard for the hybrid energy storage system to suppress power fluctuations.

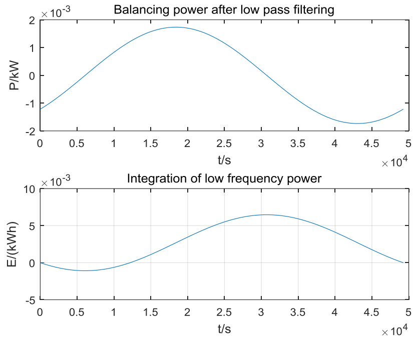
The PV data sampling period is 1 s and the sampling frequency is 1 Hz. This study uses sodium-sulfur batteries, lithium batteries, and EDLC. Their parameters are shown in the following Table 4-1.

Table 4-1 ESS type and response time

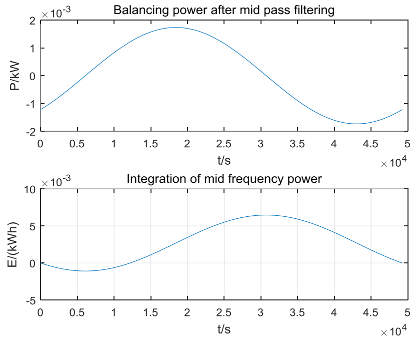
Energy storage type	response time
Lithium battery	1min-5hr
Lead-acid battery	10s-3hr
EDLC	1ms-1hr

High-, medium-, and low-frequency hybrid energy storage systems consist of EDLC, lead-acid batteries, and sodium-sulfur batteries. The particle optimization algorithm is used to find the optimal cut off points. The low and middle frequency cutoff points are used to divide frequency between the lead-acid storage battery and sodium-sulfur battery. The compensation frequency band is 0.0252. The middle and high frequency split points are used to divide frequency between lead-acid batteries and EDLC. The cutoff point is 0.0255.

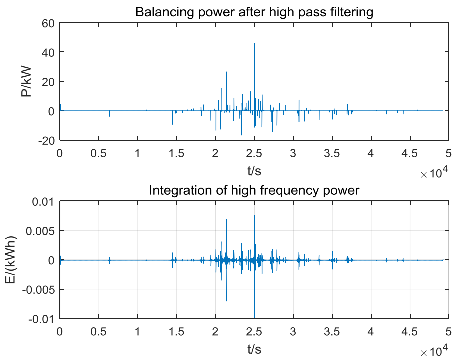
After dividing the frequency, the high, medium and low frequency components can be counted according to the daily power and energy respectively. The total power is the power of each frequency point; the energy is the power integral of all the points before each frequency point. Take 80% as an example, power and energy of high, medium and low frequency components are shown in Figure 4-2.



(a) Power and energy in low frequency



(b) Power and energy in middle frequency



(c) Power and energy in high frequency

Figure 4-2 Power and energy in low, middle and high frequency

Calculate the corresponding power and energy costs based on the energy and power unit prices in the following table. The following calculations are based on 80%.

The energy and power cost of the storage in low, middle and high frequency [31]:

$$\begin{aligned}&\textit{Low frequency battery energy cost}\ (\$)\\&=\ \textit{Unit Cost storage}(\$/kWh)\times E(kWh)\\&=\ 200\times 0.0175=3.5(4-1)\end{aligned} \quad (4\text{-}7)$$

$$\begin{aligned}&\textit{Low frequency battery power cost}\ (\$)\\&=\textit{Unit Cost storage}(\$/kW)\times P(kW)\\&=300\times 0.0920=27.6(4-2)\end{aligned} \quad (4\text{-}8)$$

$$\begin{aligned}&\textit{Mid frequency battery energy cost}\ (\$)\\&=\ \textit{Unit Cost storage}(\$/kWh)\times E(kWh)\\&=\ 300\times 2.1697\text{e-}05=6.5\times \text{e-}03(4-1)\end{aligned} \quad (4\text{-}9)$$

$$\begin{aligned}&\textit{Mid frequency battery power cost}\ (\$)\\&=\textit{Unit Cost storage}(\$/kW)\times P(kW)\\&=300\times 3.1210\text{e-}04=93.6\times \text{e-}03(4-2)\end{aligned} \quad (4\text{-}10)$$

$$\begin{aligned}&\textit{High frequency battery energy cost}\ (\$)\\&=\ \textit{Unit Cost storage}(\$/kWh)\times E(kWh)\\&=\ 2000\times 0.0048=9.6(4-1)\end{aligned} \quad (4\text{-}8)$$

$$\begin{aligned}&\textit{High frequency battery power cost}\ (\$)\\&=\textit{Unit Cost storage}(\$/kW)\times P(kW)\\&=300\times\ 14.1380=4241.4(4-2)\end{aligned} \quad (4\text{-}11)$$

Revise capacity in low, middle and high frequency:

$$costElow(1,1) < costPlow(1,1) \quad (4\text{-}12)$$

$$Elow(1,1) = Plow(1,1) * (3/2) = 0.138 \quad (4\text{-}13)$$

$$\cos tEmid\left(1,1\right) < \cos tPmid\left(1,1\right) \quad (4\text{-}14)$$

$$Emid\left(1,1\right) = Pmid\left(1,1\right) * (10/3) = 10.4 \times \text{e-03} \quad (4\text{-}15)$$

$$\cos tEhigh\left(1,1\right) < \cos tPhigh\left(1,1\right) \quad (4\text{-}16)$$

$$Ehigh\left(1,1\right) = Phigh\left(1,1\right) * (3/20) = 2.1207 \quad (4\text{-}17)$$

Energy stored by PV station in 15 years,

$$Elowbattery(1,1)=\max(positive1(N,1),negative1(N,1))=6.2866\text{e+}04 \quad (4\text{-}18)$$

$$Elowstation(1,1)=Ehighbattery(T,1)*365*15/3600= 9.5609\text{e+}04 \quad (4\text{-}19)$$

$$Emidbattery(1,1)=\max(positive1(N,1),negative1(N,1))=3.9110\text{e+}03 \quad (4\text{-}20)$$

$$Emidbattery(1,1)=\max(positive1(N,1),negative1(N,1))= 5.9481\text{e+}03 \quad (4\text{-}21)$$

$$Ehighbattery(1,1)=\max(positive2(N,1),negative2(N,1))=2.8689\text{e+}05 \quad (4\text{-}22)$$

$$Ehighstation(1,1)=Ehighbattery(T,1)*365*15/3600= 4.3631\text{e+}05 \quad (4\text{-}23)$$

Cost of storage in low, middle and high frequency,

$$Ebatterylow(1,1) = Elow(1,1) * 2500 * (1 - 0.9996^{2000}) / 2 = 1.8852\text{e+}04 \quad (4\text{-}24)$$

$$Ebatterymid(1,1) = Emid(1,1) * 5000 * (1 - 0.9996^{2000}) / 2 = 342.6825 \quad (4\text{-}25)$$

$$Ebatteryhigh(1,1) = Ehigh(1,1) * 250000 * (1 - 0.999996^{100000}) / 2 = 8.4039\text{e+}05 \quad (4\text{-}26)$$

Change time in low, middle and high frequency,

$$changelow(1,1) = Elowstation(1,1) / Ebatterylow(1,1) = 5.0716 \quad (4\text{-}27)$$

$$changemid(1,1) = Emidstation(1,1) / Ebatterymid(1,1) = 17.3573 \quad (4\text{-}28)$$

$$changehigh(1,1) = Ehighstation(1,1) / Ebatteryhigh(1,1) = 0.5192 \quad (4\text{-}29)$$

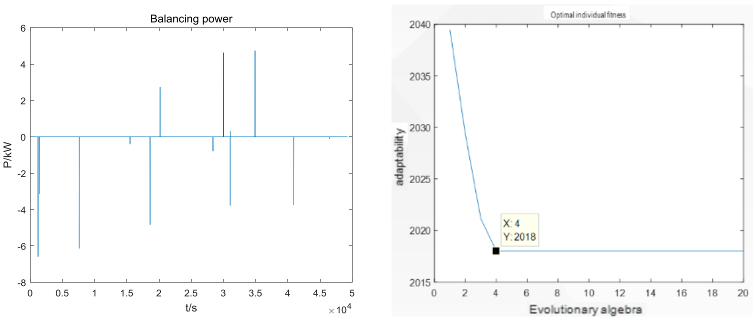
ESS actual power capacity should be oversized to meet energy capacity requirement. In this case, the actual ES power capacity is no longer the calculated value, it becomes

$$
\begin{aligned}
& cost \\
& = changelow(1,1) * costlow(1,1) + costhigh(1,1) + changemid(1,1) * costmid(1,1) \\
& = 2.8042e{+}05
\end{aligned} \quad (4\text{-}30)
$$

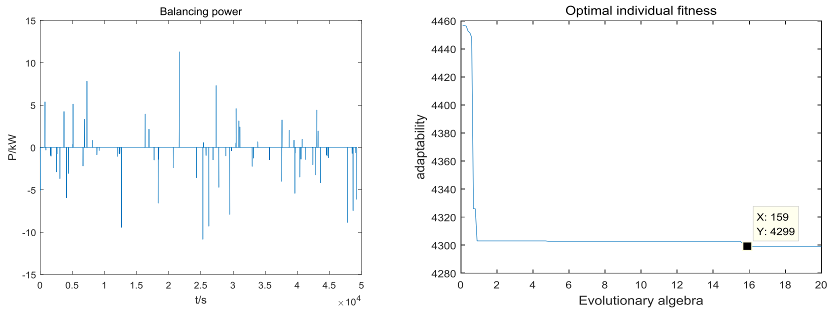
Chapter 5 Case study and Analysis

5.1 Case study

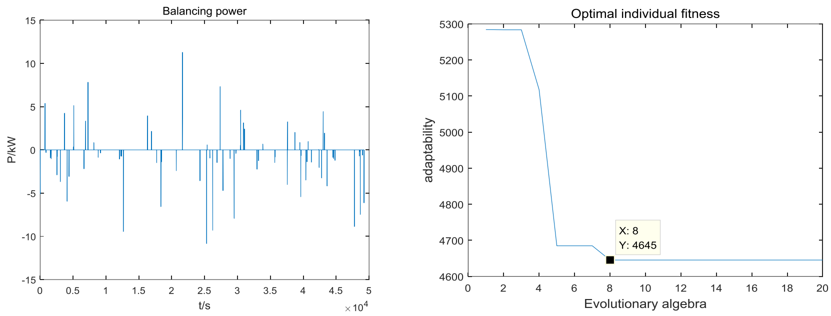
The following figures are for meeting 75% of the weather conditions and meeting 100% of the weather conditions. The price has increased in turn, and prices have changed drastically between 85% and 90%. According to the weather conditions that meet 85% of the weather, the cost for the PV configuration is $4299, and for the PV configuration that meets 90% of the weather, the cost is $16870. Moreover, the cost difference in all data is as high as 100 times, which means that the largest 15% of all PV balance data represents the extremely intense light intensity change, which is also not typical. If you don't store all the energy when you configure the capacity of the energy storage battery, and only store the minimum 85% of the energy, although the remaining 15% of the PV is not used but is abandoned, the initial cost of configuring energy storage batteries has been saved by nearly 100 times. This is considerable.



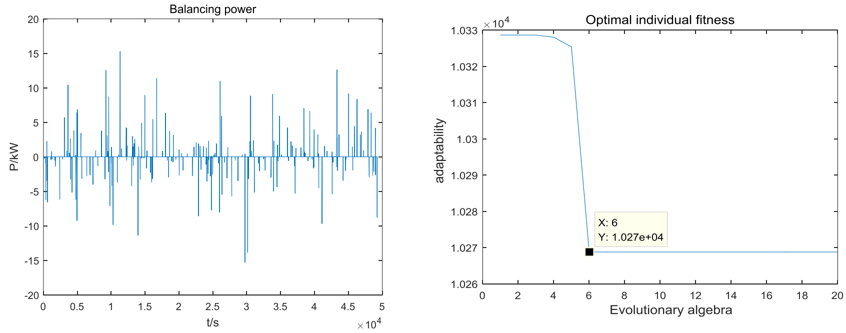
(a) Balancing power and cost of 75%



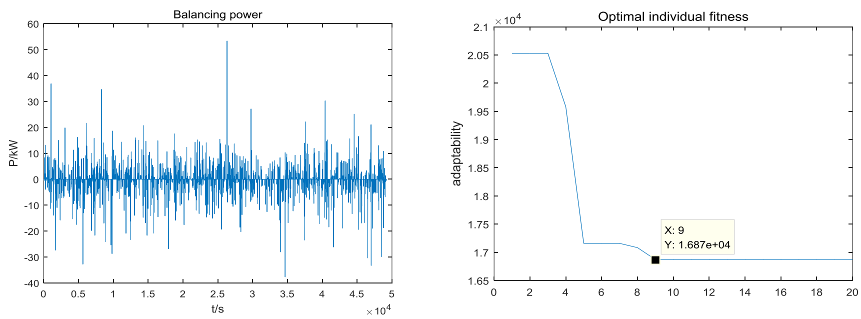
(*b*) Balancing power and cost of 80%



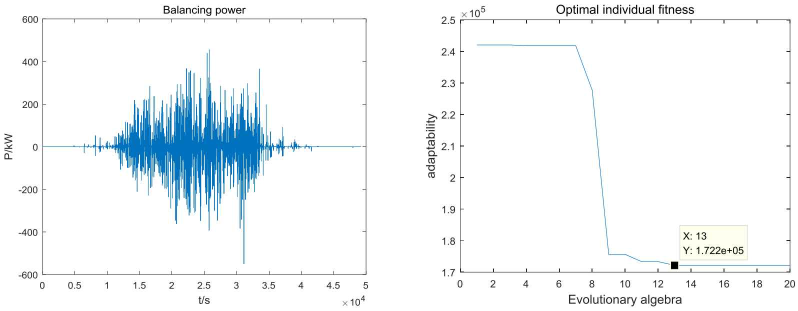
(*c*) Balancing power and cost of 85%



(*d*) Balancing power and cost of 87%



(*e*) Balancing power and cost of 90%



(*f*) Balancing power and cost of 100%

Figure 5-1 Balancing power and cost of different percentage

5.2 Comparative analysis

The capacity configurations of the above hybrid energy storage systems are the optimization results. Therefore, in each percentage mode, the result is the configuration of the energy storage capacity under the most preferred type (that is, the lowest total system cost). Comparing various energy storage combinations, the total cost of the hybrid energy storage system that meets 100% of all weather conditions is the highest. At this time, the optimal cutoff point is 1.0e-03*(0.01~0.3103)H_Z. The response frequency band of lead-acid batteries and lithium batteries is [0, 0.0167]H_Z, which is far greater than the cutoff point. At this time, the number of lithium batteries in the system is small, and the power frequency band that the EDLC need to compensate is very long. In addition, the fluctuation of power in this frequency band is large, which greatly increases the amount of EDLC, and therefore the system economy is poor. The PV configuration that meets 85% of the weather conditions is a high-, medium-, and low-frequency hybrid energy storage system composed of EDLC, lead-acid batteries, and sodium-sulfur batteries. Since the equilibrium power fluctuations within the compensation frequency range of each energy storage device are relatively uniform, the power density and energy density ratio of the balanced power within the optimal compensation band is close to that of the energy storage device. This effectively reduces the waste caused by over-dilation caused by unbalanced energy storage capacity, so it has obvious economic advantages.

The optimal cutoff points obtained in the 80% case are 0.0225Hz and 0.0255Hz, and the 100% optimal cutoff points are 1.0e-03*(0.01~0.3103)Hz. In principle, the best means the cutoff points with the lowest cost, and the 100% price must be greater than the 100% price at other frequencies. In order to verify the effectiveness of the optimization algorithm, using 80% of the optimal frequency as the cutoff points to calculate the 100% price must be greater than the 100% optimal cost. The experiment proves to be true, the price that satisfies 100% of the weather condition at the cutoff point at 80% is $2.8042e+05, far greater than optimal cost of 100% at $1.722e+05.

Chapter 6 Conclusion and Future Work

6.1 Conclusion

In order to suppress the fluctuation of PV output power in a hybrid energy storage system, this paper proposes a capacity optimization design method based on spectrum analysis, which solves the disadvantages of higher economic costs in other studies. The method and results of the optimized configuration of the hybrid energy storage system (ESS) proposed in this paper are verified by practical examples.

(1) Based on frequency. The percentile method can effectively identify the most necessary energy stored in PV.

(2) The cost cover all statues will expensive a lot than just cover the most frequently used energy storage capacity. So percentage method guarantees economy while ensuring reliability.

6.2 Future work

Based on frequency domain analysis, this research presents an ESS optimization method that suppresses PV output fluctuations. Due to the limited research time and personal capabilities of this subject, there are still some areas that require deep thinking. Follow-up related work can be completed from the following aspects:

(1) When the energy storage system optimizes the cost, the charging and discharging current of the energy storage device during the actual operation will affect its cycle life and can be properly considered. The actual initial SOC value of energy storage can be adjusted and corrected according to the regional light intensity characteristics, making the capacity configuration more accurate and reasonable.

(2) The volt-power data used in the analysis are few. Follow-up work can be performed on the PV data of the whole year and combined with temperature to obtain the most representative PV fluctuation power, or the calculation examples can be optimized considering the occurrence probability of each frequency PV fluctuation.

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