Optimal capacity allocation of multiple energy storage considering microgrid cost

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Abstract. Proper capacity of energy storage is conducive to the promotion of the economy and flexibility of the microgrid system with distributed power supply. In order to determine the size of the energy storage capacity of the whole microgrid, a method for optimal allocation of multiple energy storage capacities is presented. Based on the spectrum analysis, the power demand is divided into different frequency components. According to the response time of each energy storage, the stabilizing frequency bands are attained. According to the economy of the microgrid, the optimal stabilizing frequency bands of each storage are got based on differential evolution algorithm, then the optimal capacity and power of hybrid energy storage are attained. The results show that system annual comprehensive cost of multiple-storage microgrid is lower than two or single energy storage. Capacity optimization considering the microgrid cost is better to improve the economic efficiency of microgrid.

1. Introduction

In order to coordinate the relationship between the large power grid and distributed power supplies, the concept of the microgrid has been proposed in Ref. [1, 2]. Microgrid has the features of giving full play to the advantages of distributed power supply, energy cascade utilization and flexible operation modes. It has become one of the hot spots in grid research and development [3-5]. Energy storage plays an important role in the microgrid. It not only coordinates the power balance of the microgrid, but also filters the harmonic currents caused by non-linear load injection [4]. On the one hand, the new energy source is connected to the grid, and on the other hand, the distributed power supply is turned into a controllable power source. However, at present, the cost of various distributed power supplies and energy storage systems is high, and the economics of devices have become a bottleneck that hinders their application and development. Therefore, for microgrids and energy storage systems, it is particularly important to optimize their capacity based on economics.

Regarding the optimal configuration of energy storage capacity in the microgrid, some research results have been achieved at home and abroad. Ref. [6] used empirical mode decomposition techniques to divide the frequency of the fluctuating power supply and used a neural network model to optimize the capacity of the HESS, but it did not consider the operation of energy storage itself; Ref. [7, 8] used the Fourier transform to perform spectrum analysis on the balanced power and set the compensation sections for each energy storage. Ref. [8] also considered the impact of the operating characteristics of the energy storage equipment on its cycle life, and proposed an coordinate the power distribution strategy of the battery and supercapacitor microgrid system; Ref. [9] proposed a new type of composite energy storage system composed of compressed air energy storage, storage battery and
super capacitor, and designed an energy management distribution strategy based on smooth control, without considering the operating characteristics of each energy storage; Ref. [10, 11] discussed the optimization of microgrid energy including electric vehicles; Ref. [11] proposed an engineering configuration method for microgrid energy storage capacity of electric vehicles, and introduced the risk value theory into the risk assessment of microgrid energy storage capacity. Ref. [12] assessed an optimal energy storage capacity from the standpoint of preventing micro-grid instability and system breakdown; Ref. [13] considered the reliability and economy, and proposed that the microgrid operating cost and the energy storage operating cost will affect each other. The microgrid operating cost should be added to the optimization goal of the energy storage, but only for a single energy storage, without considering the hybrid energy storage that is now widely used.

In the above studies, for the optimization of energy storage capacity in microgrids, most of them only considered the economics of energy storage itself and did not consider the economics of the entire microgrid. Moreover, with the hybrid energy storage, the collocation type is relatively fixed, and most of them are hybrid energy storage composed of a super capacitor and a battery, without considering more types of hybrid energy storage. To solve the above problems, this paper proposes an optimized configuration method for three types of energy storage capacity considering the cost of the micro-grid. The energy storage of different response times corresponds to the power requirements of different frequencies, three kinds of energy storage corresponding to different power requirements, which will cause differences in system economics. In addition, each type of energy storage has a certain range of response time, which corresponds to a certain frequency band. How to select different frequency bands to stabilize power demand is particularly important for optimization of energy storage capacity. This paper focuses on the consideration of different capacity configurations of multiple hybrid energy storage and considers the cost of microgrid operation for optimization. In this paper, spectral analysis is used to divide the power requirements into different frequency bands, and then the differential evolution algorithm is used to select the optimal frequency division point according to the economics of the micro-grid system so as to obtain the optimal capacity.

2. Hybrid energy storage and microgrid structure

2.1. Energy storage characteristics
Taking into account the different response times of energy storage and the need to stabilize the output power fluctuation of the microgrid, energy storage with large difference in duration and response time can be selected as part of hybrid energy storage. According to Ref. [14], hydrogen with high energy density can play an important role in the micro-grid. It can be used for long-term energy storage needs, but the response time is longer, but the super capacitor and battery can be selected as part of hybrid energy storage. Therefore, this paper selects supercapacitors, lithium batteries, and hydrogen to constitute a hybrid energy storage, in which the hydrogen storage energy is an electro-hydrogen-electrical-circulatory system, and its characteristics [15] are shown in table 1.

| Characteristic       | supercapactor | lithium battery | hydrogen     |
|----------------------|---------------|-----------------|--------------|
| Energy storage duration | Seconds to minutes | Hours to weeks | Hours to weeks |
| Energy Density (Wh/l) | 2-10          | 50-100          | 500-2,500    |
| Power density (W/l)  | 15,000-50,000 | 10-500          | -            |
| Cycle efficiency (%) | 77-83         | 70-80           | 34-40        |
| Self-discharge rate  | 25%           | 0.1-0.4%        | 0.003-0.03%  |
| life (year)          | 15            | 10-15           | 20           |
| Cycle life (frequency) | >1 million    | >10,000        | >5,000      |
| Capacity cost (yuan/kWh) | 75,000-150,000 | 2,250-3,750    | 2.2-4.5     |
| Power cost (yuan/kW)  | 1,125-1,500   | 7,500-11,250    | 11,250-15,000 |

It can be seen that the power density of the supercapacitor is relatively large, the power cost is correspondingly smaller, the energy density of hydrogen is larger, the capacity cost is correspondingly
smaller, and the lithium battery is centered. The lifetime of the supercapacitor and hydrogen is relatively fixed, and the lifespan of the lithium battery can be changed within a certain range depending on its use.

2.2. Hybrid energy storage operation model

The service life of supercapacitors and hydrogen storage is relatively fixed, and lithium batteries are affected by their use. The life of a lithium battery is mainly affected by its depth of discharge, the number of cycles of charge and discharge, etc. The equivalent number of charge and discharge times can be obtained according to the cycle life corresponding to different depths of discharge, and the service life can be obtained. The equivalent cycle number of the i-th discharge of a lithium battery [7] is:

\[ N_{eq}(d_i) = \frac{N_{SB}(d_b)}{N_{SB}(d_i)} = \left( \frac{d_i}{d_b} \right)^{0.19} e^{1.69 \frac{d_i}{d_b}} \]  

(1)

In the formula, \( d_b \) is the reference depth of discharge, \( d_i \) is the actual depth of the i-th discharge.

\[ N(x) = \sum_{i=1}^{D} \sum_{m=1}^{T} N(d_{im}, x) \]  

(2)

In the formula, \( D \) is the number of days that the battery is charged and discharged in year \( x \), and \( T \) is the number of equivalent charge and discharge cycles in one day, and \( N(d_{im}, x) \) is the number of equivalent cycles in the m-th charge and discharge of the battery on the first day.

Therefore, the service life \( Y_B \) of a lithium battery is:

\[ Y_B = \frac{N_{SB}(d_b)}{N(x)} = \frac{N_{SB}(d_b)}{\sum_{i=1}^{D} \sum_{m=1}^{T} N(d_{im}, x)} \]  

(3)

Table 2 shows the response time of the three types of energy storage and their stabilizing frequency bands. In this paper, 10s is selected as the fastest response time of the system, taking into account that the rise time in the sinusoidal signal is a quarter of the cycle time [16], and its corresponding frequency is 1/40Hz.

| Energy storage type       | Response time | Corresponding frequency band |
|---------------------------|---------------|-----------------------------|
| Supercapacitor            | 10s-1min      | 1/40-1/240Hz                |
| Lithium battery           | 50s-10min     | 1/200-1/2,400Hz             |
| Hydrogen                  | >7min         | <1/1,680Hz                  |

2.3. Microgrid system structure

Figure 1 shows a stand-alone microgrid system based on supercapacitor-lithium cell-hydrogen hybrid energy storage. Supercapacitors, lithium batteries, and hydrogen are connected to the AC bus through inverters, respectively, to charge and discharge the system to smooth intermittent power supply and load fluctuations.

![Figure 1. Structure of microgrid system.](image)
In the figure, $P_{MT}$ is the microturbine (MFT) output power, $P_{PV}$ is the photovoltaic generation output power, $P_W$ is the wind power generation output power, $P_B$ is the lithium battery output power, $P_F$ is the supercapacitor output power, $P_I$ is the hydrogen storage output power, $P_H$ is Mixed energy storage output power, $P_L$ is load power.

3. Hybrid energy storage capacity optimization model in microgrid

This paper establishes an optimal energy storage capacity model that takes the annual minimum total cost of the microgrid as the objective, and considers power, capacity constraints, and microgrid reliability constraints, and uses the differential evolution algorithm to obtain the optimal frequency division point and obtain the most Excellent energy storage capacity.

3.1. Objective function

In order to optimize the economical efficiency of the microgrid system, this paper takes the annual minimum cost of the microgrid system $C_{total}$ as the objective function. The annual comprehensive cost of the system $C$ includes the annual value of the microgrid construction cost, the annual value of the microgrid operation, the annual value of $c$ cost, and the annual value of the penalty cost, etc. The expression is as follows:

$$\min \; C_{total} = C_D + C_Y + C_{LOST}$$

(4)

In the formula, $C_D$ is the annual value of the microgrid construction cost, $C_Y$ is the annual value of the microgrid operation and maintenance cost, and $C_{LOST}$ is the sum of the penalty power interruption penalty cost and the abandoned scenery cost.

1) The annual value of microgrid construction cost:

$$C_D = C_W + C_{PV} + C_{MT} + C_B + C_F + C_I$$

(5)

In the formula, $C_W$, $C_{PV}$, $C_{MT}$, $C_B$, $C_F$, $C_I$ respectively represent the annual values of the wind power generation system, photovoltaic power generation system, microturbine (MFT), lithium battery energy storage, supercapacitor energy storage, and hydrogen storage energy construction cost.

$$C_B = (k_B P_B + k_B E_B) \frac{r(1+r)^{1B}}{(1+r)^{1B} - 1}$$

(6)

$$C_F = (k_F P_F + k_F E_F) \frac{r(1+r)^{1F}}{(1+r)^{1F} - 1}$$

$$C_I = (k_I P_I + k_I E_I) \frac{r(1+r)^{1I}}{(1+r)^{1I} - 1}$$

In the formula, $k_B$, $k_E$, $k_F$, $k_E$, $k_I$ are power cost coefficient and capacity cost coefficient of lithium battery, super capacitor and hydrogen respectively, $P_B$, $E_B$, $P_F$, $E_F$, $P_I$ and $E_I$ are the rated power and capacity of lithium battery, super capacitor and hydrogen respectively, $r$ is discount rate.

2) The annual value of microgrid total operation and maintenance cost:

Microgrid total operation and maintenance cost $C_Y$ includes the cost of power supply and maintenance $C_{YS}$ [13] and the cost of energy storage and maintenance $C_{YE}$:

$$C_Y = C_{YS} + C_{YE}$$

(7)

$$C_{YS} = C_M + C_{SUD}$$

(8)

$$C_{YE} = C_{degrch} P_{B,ch}^2 + C_{degrdis} P_{B,dis}^2 + C_{FM} + C_{BM} + C_{HM}$$

(9)

In the formula, $C_M$ is the maintenance cost of each microsource in the microgrid, $C_{SUD}$ is the start-stop cost of each micro-source, $C_{degrch}$ and $C_{degrdis}$ respectively represent the charge and discharge loss costs, $P_{B,ch}$ and $P_{B,dis}$ respectively represent the charge and discharge power, $C_{FM}$, $C_{BM}$, $C_{HM}$ respectively represent the operation and maintenance costs of supercapacitors, lithium batteries, and hydrogen.
3) The annual value of the penalty cost:

\[ C_{\text{LOST}} = k_{\text{LOST}} \int |P_{\text{LOST}}(t)| dt \]  

(10)

\[ P_{\text{LOST}} = P_L - P_{\text{MT}} - P_{\text{PV}} - P_W - P_H \]  

(11)

\( k_{\text{LOST}} \) is the penalty coefficient and \( P_{\text{LOST}} \) is the load forced power outage or the abandoned wind power.

3.2. Constraints

1) Microgrid power constraints [5]:

\[ P_{\text{MT}} + P_{\text{PC}} + P_W + P_{\text{PV}} + P_H + P_{\text{LOST}} = P_L \]  

(12)

2) Operational constraints of energy storage equipment [17]:

\[
\begin{align*}
E_{\text{Bmin}} & \leq E_B \leq E_{\text{Bmax}} \\
E_{\text{Fmin}} & \leq E_F \leq E_{\text{Fmax}} \\
E_{\text{Hmin}} & \leq E_H \leq E_{\text{Hmax}} \\
P_{\text{Bmin}} & \leq P_B \leq P_{\text{Bmax}} \\
P_{\text{Fmin}} & \leq P_F \leq P_{\text{Fmax}} \\
P_{\text{Hmin}} & \leq P_H \leq P_{\text{Hmax}}
\end{align*}
\]  

(13)

(14)

In the formula, \( E_{\text{Bmin}}, E_{\text{Bmax}}, E_{\text{Fmin}}, E_{\text{Fmax}}, E_{\text{Hmin}}, \) and \( E_{\text{Hmax}} \) respectively represent the upper and lower limits of the lithium battery, supercapacitor, and hydrogen storage remaining charge, \( P_{\text{Bmin}}, P_{\text{Bmax}}, P_{\text{Fmin}}, P_{\text{Fmax}}, P_{\text{Hmin}}, P_{\text{Hmax}} \) respectively represent the upper and lower power limits for the lithium battery, supercapacitor, and hydrogen storage charge and discharge processes. In this paper, the upper and lower limits for the remaining energy of the stored energy are \( 0.9 E_N \) and \( 0.1 E_N \).

3) Reliability constraints[18]:

In this paper, the probability of power shortage in isolated islands \( \xi_{\text{CPDNSI}} \) is considered as a reliability constraint, which is defined as:

\[ \xi_{\text{CPDNSI}} = \Pr \{ P_s \leq P_L \} \]  

(15)

In the formula, \( P_s \) is the sum of the active contributions of all power sources in the microgrid. This paper uses a statistical method to calculate. Specific statistics should satisfy: with a certain period of time \( T \), count all the time periods that satisfy \( P_s \leq P_L \), and then sum them to obtain the time \( T_s \).

\[ \xi_{\text{CPDNSI}} = T_s / T \]  

(16)

4. Solution Algorithm

4.1. Power analysis strategy based on spectrum analysis

Spectrum analysis is a method of converting a time domain signal into a frequency domain signal. Let \( x(t) \) be a continuous time domain signal, the sampling period is \( T_s \), the sampling frequency is \( f_s \), and the number of samples is \( m \). According to the sampling theorem, \( m \) should be greater than twice the highest frequency in the signal [8], and the total sampling period is \( m T_s \). Perform a discrete Fourier transform on \( x(v)(v = 1, 2, \ldots, m) \) to obtain amplitude \( \delta(k)(k = 1, 2, \ldots, m) \) and the corresponding frequency \( f(k) \) [19]:
The spectrum diagram is a symmetric graph with the symmetry axis of the Nyquist frequency which is $f_s/2$. The complex sequences on both sides are conjugate and magnitudes are equal to each other. Therefore, only the spectral characteristics in the range $[0,f_s/2]$ are considered [19]. The actual amplitude $\delta(k)_{\text{real}}$ corresponding to the spectrum amplitude $\delta(k)$ [20]:

$$
\delta(k)_{\text{real}} = \begin{cases} \\
\frac{|\delta(k)|}{m} & k = 0 (m \text{ is odd}) \\
\frac{|\delta(k)|}{m} & k = 0, m, \frac{m}{2} (m \text{ is even}) \\
\frac{|\delta(k)|}{m} & k = 0, m, \frac{m}{2} (m \text{ is odd}) \\
\frac{|\delta(k)|}{m} & k = 0, m, \frac{m}{2} - 1 (m \text{ is even}) \\
\end{cases}
$$

(18)

$|\delta(k)|$ is the magnitude of $\delta(k)$; $\left\lfloor \frac{m}{2} \right\rfloor$ is the rounding of $\frac{m}{2}$.

According to Pasayval’s theorem, the energy of the signal in the frequency band $[f(k),f(k+1)]$ ($i = k, \cdots, m$) is [18]:

$$
E(f(k), f(k+1)) = \sum_{j(k)} |\delta(f)|^2
$$

(19)

According to the sampling theorem, the sampling frequency should be greater than twice the highest frequency in the signal. This paper selects 10s as the fastest response time of the system. The corresponding time is 20s and the sampling frequency is $1/20$Hz to meet the sampling requirements.

Combined with spectrum analysis, the specific steps for power allocation are as follows:

1) Calculate the net load, which is the difference between the actual load and the power generation. The formula is as follows:

$$
P_{\text{net}} = P_L - P_{MT} - P_{PV} - P_W
$$

(20)

2) Perform a DFT transform on the net load to obtain the amplitude of the net load in the frequency domain and the corresponding frequency, as in equation (17);

3) According to equation (18), the actual amplitude of the net load is obtained, and the energy of each frequency band is calculated according to equation (19);

4) According to the compensation band of each energy storage, the range of selection of the frequency division point for each energy storage distribution power is determined, and the capacity allocated to each energy storage is obtained.

4.2. Capacity optimization algorithm

The problem to be solved in this paper is the nonlinear problem of multiple decision variables. The variables include the power of each energy storage and two frequency division points. It is proposed to use the differential evolution algorithm.

Differential evolution algorithm is a kind of greedy choice algorithm based on real number coding and has the idea of survival and elimination of the fittest [21]. Starting from a randomly generated initial population, it gradually approaches the optimal solution through crossover, mutation, and selection. It has the characteristics of optimal solution memory and information sharing within the
population, as well as better global search capability. The total flow chart of the model combined with spectrum analysis is shown in figure 2.

![Flow chart of differential evolution algorithm based on spectrum analysis](image)

**Figure 2.** Flow chart of differential evolution algorithm based on spectrum analysis.

5. Example analysis

5.1. Basic data
This paper takes the actual distributed power supply and load data of a microgrid in an area as an example to verify the accuracy and validity of the above capacity configuration method. Based on the original data, that is, the predicted value of wind power generation, photovoltaic power generation and load power for one year [22], the part requiring energy storage system compensation is obtained from the perspective of continuous supply of microgrids.

Power supply and energy storage parameters [14, 15, 21] are shown in table 3. The discount rate is set to 0.06, the penalty factor is 500 yuan/kW·h, and the LOLP is 0.02. In the differential evolution algorithm, the population size is set to 20, the individual length is set to 20, the crossover factor is set to 0.5, and the variation factor is set to 0.4.

| Objects          | Unit power cost (yuan/kW) | Unit capacity cost (yuan/kWh) | Charge efficiency (%) | Discharge efficiency (%) | Startup cost (yuan) | Stop cost (yuan) | Loss cost (yuan/kW·h) | Maintenance cost (yuan/kW·h) | Life (year) |
|------------------|--------------------------|-------------------------------|-----------------------|--------------------------|---------------------|------------------|----------------------|----------------------------|------------|
| lithium battery  | 11,250                   | 3,750                         | 0.90                  | 0.95                     | -                   | -                | 10-9                 | 0.05                       | 10-15      |
| supercapactor    | 1,500                    | 75,000                        | 0.97                  | 0.99                     | -                   | -                | -                    | 0.042                      | 15         |
| Hydrogen storage | 14,000                   | 4.5                            | 0.34                  | 0.40                     | 0.995               | 8.3*10^-5        | 0.45                 | 0.023                      | 20         |
| Photovoltaic system | 20,000               | -                              | -                     | -                        | -                   | -                | -                    | 0.054                      | 20         |
| Wind power system | 12,000                 | -                              | -                     | -                        | -                   | -                | -                    | 0.067                      | 10         |
| MFT              | 10,000                   | -                              | -                     | -                        | 3                   | 9*10^-3          | -                    | 0.040                      | 10         |

5.2. Optimization process and results
Figure 3 shows the actual spectrum of the net load. It can be observed that the low frequency component is large and the high frequency component is small. The sampling frequency of this paper is 1/20Hz, which corresponds to the highest frequency in the figure.
Figure 3. The spectrum of net load.

According to table 2, the supercapacitor overlaps the lithium battery in the [1/240Hz, 1/200Hz] band, and the lithium battery overlaps with hydrogen in the [1/2400Hz, 1/1680Hz] band, corresponding to data points [162, 195] and [17, 24] Get the choice of two crossover points. The system annual comprehensive cost obtained by selecting crossover points in these two ranges is shown in figure 4. It can be observed that the overall total cost of the system corresponding to the lower crossover points is smaller.

Figure 4. System annual comprehensive cost with the change of frequency division point.

The results obtained by the differential evolution algorithm are consistent with the results shown in the figure. The first frequency divider is 1/240 Hz and the second frequency divider is 1/2400 Hz. Other results are shown in configuration 1 in table 4. Configuration 2 is the capacity optimization of the supercapacitor-lithium battery hybrid energy storage. Considering the response frequency band of these two types of energy storage, select [1/240Hz, 1/120Hz] as the crossover point selection range, and configure 3 as the capacity optimization of the lithium battery. It can be observed that the total integrated cost of the microgrid containing three types of energy storage is the smallest, that is, the economical efficiency is the best. Followed by two kinds of energy storage, single storage energy is the worst. Among the three types of energy storage, hydrogen has the lowest cost of capacity, and the use of hydrogen of a suitable capacity can reduce the total cost of the system. Therefore, the total cost of configuration 1 is the lowest. The single storage energy of configuration 1 does not have the advantages of various energy storage costs and different capacity costs when compared to mixed energy storage. The response time is limited and the penalization cost is large. Therefore, the total cost is the highest. According to figure 5, it can be seen that no matter how $\xi_{\text{CPDNSI}}$ changes, the annual comprehensive cost of the three energy storage systems is always smaller than the other two configurations, and with the increase of $\xi_{\text{CPDNSI}}$, the gap is increasing.

Table 5 shows the system-related parameters with or without considering the cost of the microgrid. When considering the cost of the micro-grid, the annual comprehensive cost of the system is relatively
low when it is not considered, the penalization cost of the micro-grid changes greatly because the cost of the micro-grid is not considered. Energy storage can not better coordinate the operation of the microgrid. Although the cost of the energy storage system is reduced, the cost of the entire system is increased.

Table 4. Optimization results of three kinds of energy storage configurations.

| parameter                              | Configuration 1 | Configuration 2 | Configuration 3 |
|----------------------------------------|-----------------|-----------------|-----------------|
| Annual total cost /yuan                | 2.2063*10⁷      | 2.2284*10⁷      | 2.8163*10⁷      |
| Annual total construction cost /yuan    | 1.6386*10⁷      | 1.6569*10⁷      | 2.1595*10⁷      |
| Annual total operation and maintenance cost /yuan | 3.4873*10⁶      | 3.5249*10⁶      | 4.0131*10⁶      |
| Power operation and maintenance cos/yuan| 1.9403*10⁴      | 1.9403*10⁴      | 1.9403*10⁴      |
| Energy storage and maintenance costs /yuan | 3.4679*10⁶      | 3.5055*10⁶      | 3.9937*10⁶      |
| Annual total penalty cost /yuan         | 2.19*10⁶        | 2.19*10⁶        | 2.5550*10⁶      |
| Supercapacitor rated power /kW         | 3.3365*10³      | 3.3177*10³      | -               |
| Supercapacitor rated capacity /kW·h    | 1.5611*10⁴      | 1.5518*10⁴      | -               |
| Lithium battery rated power /kW        | 556.4243        | 621.7387        | 3.3045*10³      |
| Lithium battery rated capacity /kW·h   | 2.5880*10³      | 2.9717*10³      | 1.8236*10⁵      |
| Hydrogen storage rated power /kW       | 71.6151         | -               | -               |
| Hydrogen storage rated capacity /kW·h  | 290.3852        | -               | -               |

Figure 5. Annual comprehensive cost of three configurations under different $\xi_{\text{CPDNSI}}$.

Table 5. System related parameters in two cases.

|                          | Energy storage maintenance cost /yuan | Power operation and maintenance cost /yuan | Microgrid total cost /yuan | Microgrid penalty cost /yuan |
|--------------------------|--------------------------------------|-------------------------------------------|---------------------------|-----------------------------|
| Considering the microgrid cost | 3.47*10⁶                            | 1.94*10⁴                                  | 2.01*10⁷                  | 2.19*10⁶                    |
| Without considering the microgrid cost | 3.19*10⁶                            | 1.97*10⁴                                  | 2.79*10⁷                  | 4.19*10⁶                    |

Figure 6 is a plot of the system's annual overall cost as a function of the second frequency division point when the first crossover point equals 1/2400 Hz. It can be stated that the use of spectrum analysis alone cannot determine the optimal energy storage capacity, and it should be combined with the differential evolution algorithm to find the optimal frequency division point and then obtain the optimal energy storage capacity.
6. Conclusions

In this paper, considering the characteristics of energy storage operation and the cost of the microgrid, spectrum analysis and differential evolution algorithm are used to optimize the energy storage capacity for the microgrid system. Based on the spectrum analysis of the net load of the microgrid, according to the three frequency bands of energy storage, this paper proposes a power allocation strategy for coordinating three kinds of energy storage and microgrid. This paper also establishes an optimal energy storage capacity model that takes the annual minimum total cost of the microgrid as the objective, and considers power, capacity constraints, and microgrid reliability constraints, and uses the differential evolution algorithm to obtain the optimal frequency division point and obtain the most Excellent energy storage capacity. The example shows that the microgrid system under three types of energy storage is more economical.

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