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Energy storage device locating and sizing based on power electronic transformer

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Abstract: In this study, firstly, the bi-directional energy flow of grid-connected photovoltaic and energy storage system based on power electronic transformer is demonstrated. Based on this, a bi-level programming model is proposed for the location and capacity of energy storage. The optimisation of the location of the outer layer is based on the improved particle swarm algorithm. The energy storage location is a variable, and network loss as well as PET loss are objective functions. The improved particle swarm optimisation algorithm is still adopted to optimise the capacity in the inner layer. The cost of electricity from the main grid is taken as the objective function, and the economic dispatch is realised based on the energy routing strategy of power electronic transformer.

1 Introduction

Power electronic transformer (PET) is a new device of distribution transformer in recent years, which uses power electronic converter technology. The most commonly used structure of PET is AC–DC–AC, which is to rectify the power frequency AC into DC, then invert it into high-frequency alternating current, and use high-frequency transformer to realise the transformation of voltage and current. Finally, the high-frequency AC is converted to power frequency AC and DC. PETs have both DC and AC links, which can provide interface for DC power supply and DC load and facilitate the access of various distributed power sources. Another important feature of PET is the realisation of energy routing, which can provide a more flexible way of power supply and distribution and flexibly adjust the power flow of the system, specifically as follows: (i) the trend on each line can be flexibly controlled bi-directionally and real-time adjustment can be realised; (ii) the voltage on each bus can be controlled independently so as to realise the optimal operation of the system; (iii) to achieve plug and play coordinated operation of new energy and energy storage devices under various modes; (iv) to cooperate with energy storage devices to achieve optimal configuration of various objectives. Therefore, more and more distributed new energy access to power grids and the emergence of AC–DC hybrid power distribution network put forward a great demand for PETs [1, 2].

The renewable energy in micro-grid has obvious intermittency and volatility, and its output power is greatly influenced by the weather changes. Moreover, the load fluctuates regularly with time, resulting in the power fluctuation of power grid, and then causes voltage fluctuation and power quality problems.

Energy storage system has played a great role in smoothing intermittent energy power fluctuation, cutting peak and valley filling, improving voltage quality, and providing backup power supply, because of its fast power regulation and storage capacity. Therefore, by utilising the power regulation means of the energy storage device and the power flow distribution function of the PET, it is possible to realise the friendly connection between the micro-grid and its renewable energy and the distribution network. In this paper, the micro-grid with photovoltaic and energy storage is the research object.

The configuration of battery capacity has a great impact on photovoltaic power generation. If the capacity is too large, it will not only increase investment and the battery will be in a state of insufficient charge for a long time, affecting the use effect and life span of energy storage and cannot achieve its economy [3]. If the capacity is too small, the PV system cannot fully realise the economic benefits, and the power supply reliability of the power grid is reduced. Therefore, the capacity configuration of the battery is the key to determine whether the grid system can be stable, efficient, and economical. At present, there are many ways to determine the capacity of energy storage. In [4], a hybrid energy storage capacity allocation method based on opportunity constrained programming is proposed, aiming at the lowest cost of equipment. Zhou *et al*. [5] proposed two indexes for evaluating active power fluctuation from the point of view of storing energy to stabilise the output power fluctuation of the storage system, and optimised the energy storage capacity. However, there is no article on PET-based energy storage optimisation programme, which is a key point of this paper.

2 Double-layer optimisation programme of energy storage

The research object of this paper is grid-connected photovoltaic and energy storage system based on PETs. The typical PET-based AC/DC hybrid micro-grid system is shown in Fig. 1. The main network is 10 kV distribution network, and the DC micro-grid and AC micro-grid are formed by PET connection. The distributed power supply in DC micro-grid is mainly connected to the grid by DC–DC converter. The distributed power supply in AC micro-grid is mainly connected to the grid by inverters such as DC–AC and AC–DC–AC. Photovoltaic and energy storage devices have both DC access mode and AC access mode. In this paper, photovoltaic AC access is chosen, so the access location of energy storage device is discussed. The location of energy storage will affect the power flow calculation of the network. In this paper, the improved particle swarm optimisation (PSO) algorithm is applied to the outer location optimisation, of which the objective function is line loss and PET port loss.

As the PV output power is affected by the weather, the load power also fluctuates in different time periods. The energy fluctuates frequently in the DC micro-grid and the AC micro-grid. PET acts as the ‘energy router’ and can coordinate the power flow well. The flow of energy between the network interfaces must be bi-directional, and can be quickly and accurately adjusted according to the change of the characteristic signals at the interface. In the grid-connected mode, the mixed micro-grids are divided into two working states of power consumption and power feedback. From the main network, after PET's high power quality modulation, the entire AC/DC hybrid micro-grid acts as a resistive

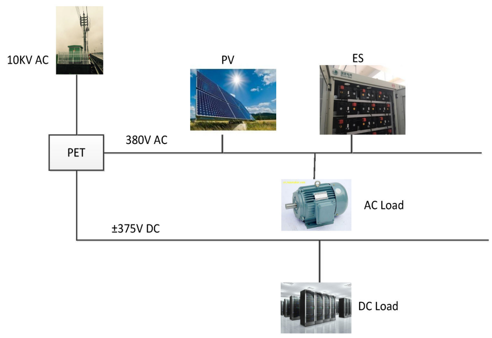

Fig. 1 *PET-based AC/DC hybrid micro-grid system*

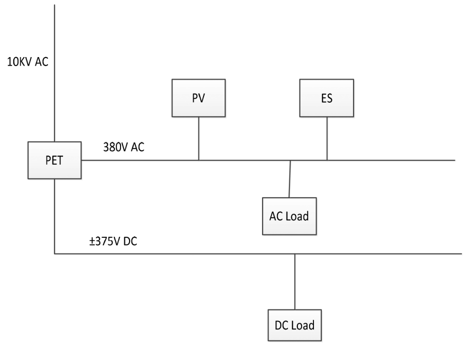

Fig. 2 *Structure diagram of the micro-grid based on PET*

load (state 1) at power consumption and as a current source (state 2) at power feedback. When working in state 1, the main grid can buffer any imbalance of power in the AC/DC hybrid micro-grid. When operating in state 2, surplus power from photovoltaic flows to the main network with guaranteed load consumption.

The charge and discharge state of the energy storage device is determined by the power state of each port of PET and the capacity of its own energy storage. Therefore, the energy storage capacity optimisation of the PET based micro-grid with photovoltaic must be carried out to determine the power control decision of the PET. The PSO algorithm is used in the optimisation of energy storage capacity in the inner layer. For users, photovoltaic cells, storage devices, and PETs are the users' inherent assets, i.e. the energy produced by photovoltaic and energy storage devices are essentially free of charge. Therefore, it is of great practical significance to minimise the cost of purchasing power from the grid through the capacity optimisation algorithm.

Double-layer energy storage optimisation process is as follows:

i. Obtaining the capacity of energy storage device by inner layer capacity optimisation algorithm.
ii. The optimal capacity obtained is substituted into the inner optimisation algorithm as a known quantity to obtain the stored energy output Pbat and the tie line power Pgrid under the optimal capacity.
iii. The objective function related to loss in the position optimisation of outer layer needs the calculation of the power flow, in which the Pbat and Pgrid used by the power flow calculation are transferred from the inner layer.
iv. The location of the energy storage device is obtained by the location optimisation algorithm of the outer layer.

3 Optimisation algorithm for location of outer layer

3.1 Line loss

Grid connected micro-grid contains photovoltaic power generation and energy storage equipment, so that the flow of branches in the power grid is no longer a single direction flow, which will cause the change of network loss. Therefore, the network loss is not only related to the power consumption of the load, but also related to the capacity of photovoltaic and energy storage. It can be divided into the following three cases:

i. The power consumption of each node is greater than the sum of the power produced by photovoltaic and energy storage of the node, which reduces the power flow of the line and reduces the loss of the network;
ii. The power consumption of at least one node is less than the total power of the PV and energy storage of the node, but the total load is greater than the total power generation of photovoltaic and energy storage. Although part of the lines increase in line loss due to power flow reversal, the overall line loss of the network will be reduced;
iii. At least one node's load is less than the sum of the photovoltaic and energy storage power of the node, and the total load is less than the total energy of the photovoltaic and energy storage. If the total power of photovoltaic and energy storage is less than two times the total load, then the net loss will still be reduced.

Thus, grid-connected micro-grid with photovoltaic and energy storage has significant loss reduction benefits. For radiated networks, the network loss is calculated as

$$P_{\text{loss}} = \sum_{i=1}^{n} \frac{P_i^2 + Q_i^2}{V_i^2} R_{ij}$$

where P_{loss} is the network loss, P_i is the injected active power of node i, Q_i is the injected reactive power of node i, V_i is the voltage amplitude of node i, and R_{ij} is the resistance of line ij. Calculating the network loss requires the calculation of the grid power flow. Therefore, we choose the relevant quantity of the network loss as the basis for the location selection of the energy storage device.

In order to measure the extent of the change in network loss, we introduce network loss sensitivity analysis. The loss sensitivity factor (LSF) of the net loss refers to the amount of change in the loss of the power grid caused by an increase of one unit of output, as shown in the following formula:

$$\text{LSF}_i = \frac{\partial P_{\text{loss}}}{\partial P_i} = 2\sum_{i=1}^{n} \frac{P_i}{V_i^2} R_{ij}$$

where LSF_i is the LSF of node i. The larger the value of LSF_i, the more obvious the network loss decreases after node i increases its output by one unit. Therefore, the objective function of outer position optimisation is

$$\min P_{\text{loss}} + 1/\text{LSF}$$

Fig. 2 is the structure diagram of the grid-connected micro-grid with photovoltaic and energy storage based on PET.

When the storage energy is connected to the 380 V AC node,

$$P_{\text{loss1}} = \frac{(P_{\text{PV}} - P_{\text{ES}} - P_{\text{AC}})^2}{380^2} R_1 + \frac{(-P_{\text{DC}})^2}{375^2} R_2 + \frac{P_{\text{grid}}^2}{10^8}$$

where P_{loss1} is the total network loss when the energy storage is connected to the 380 V AC node, P_{PV} is the PV output, P_{ES} is the energy storage output, P_{ES} is negative when the energy storage device is charged, P_{ES} is positive when the energy storage device is discharged, P_{AC} is AC load, P_{DC} is DC load, R_1 is the resistance of the 380 V AC line, R_2 is the resistance of the ±375 V DC line, P_{grid} is the power input to the micro-grid from the grid, and if the power is input from the micro-grid to the grid, the P_{grid} is negative.

When the storage energy is connected to the ±375 V DC node,

$$P_{\text{loss2}} = \frac{(P_{\text{PV}} - P_{\text{AC}})^2}{380^2} R_1 + \frac{(-P_{\text{ES}} - P_{\text{DC}})^2}{375^2} R_2 + \frac{P_{\text{grid}}^2}{10^8}$$

Table 1 Operating efficiency under different load rates

380 V–10 kVAC							
load factor	0.100	0.200	0.300	0.400	0.500	0.750	1.000
efficiency	0.892	0.937	0.958	0.963	0.964	0.960	0.951
±375 V–10 kVAC							
load factor	0.100	0.200	0.300	0.400	0.500	0.750	1.000
efficiency	0.938	0.966	0.976	0.980	0.980	0.978	0.972
±375 V–380 V							
load factor	0.100	0.200	0.300	0.400	0.500	0.750	1.000
efficiency	0.950	0.970	0.982	0.983	0.983	0.981	0.979

where P_{loss2} is the total network loss when the energy storage is connected to the ±375 V DC node.

When the storage energy is connected to the 10 kV AC node,

$$P_{\text{loss3}} = \frac{(P_{\text{PV}} - P_{\text{AC}})^2}{380^2}R_1 + \frac{(-P_{\text{DC}})^2}{375^2}R_2 + \frac{\left(-P_{\text{ES}} + P_{\text{grid}}\right)^2}{10^8}$$

where P_{loss3} is the total network loss when the energy storage is connected to the 10 kV DC node.

3.2 PET loss

As the power supply object and load are constantly changing, the input and output power of different ports in PET are also changing constantly, so the efficiency of PET operation is not constant. For PET, the efficiency of different ports is different. According to transformer theory, the operation efficiency between any two ports of PET is the ratio of output power to input power, and the operation efficiency is closely related to the load rate. The relationship between the running efficiency of PET and the load rate discussed in this paper is shown in Table 1.

Taking 380 V–10 kV AC port as an example (assuming that energy storage is connected to 380 V AC node) to explain the calculation method of PET port loss:

If $P_{\text{grid}} > 0$, the 10 kV port inputs power, the 380 V port outputs power, and the port loss is

$$P_{10-380} = (1 - \eta_{380-10}(\beta)) \cdot \left(P_{\text{grid}} - \frac{P_{DC}}{\eta_{375-10}(\beta)}\right)$$

If $P_{\text{grid}} < 0$, the 10 kV port outputs power, the 380 V port inputs power, and the port loss is

$$P_{380-10} = (1 - \eta_{380-10}(\beta)) \cdot \left(P_{\text{PV}} - P_{\text{ES}} - P_{\text{AC}} - \frac{P_{\text{DC}}}{\eta_{375-380}(\beta)}\right)$$

where η is operating efficiency, β is load rate.

The specific process of location optimisation is as follows:

i. Initialise the parameters of a particle swarm with population size N: position and velocity;
ii. Calculate the objective function value of each particle, in which the power of various devices and loads used in the power flow calculation is delivered from the inner layer optimisation;
iii. Compare the fitness value of each particle with the best fitness value it has experienced, and replace it if it is better;
iv. Compare the fitness value of the best location for each particle with the fitness value of the best place globally, and replace it if it is better;
v. Update particle parameters: position and velocity;
vi. If the maximum iteration has been reached, the best optimisation is obtained, otherwise, return to step ii to continue.

4 Optimisation algorithm for capacity of inner layer

The objective function of the optimization of energy storage capacity is the cost of electricity purchased from the grid, i.e.

$$\min C = \sum_{i=0}^{T} C_{\text{grid}}(t)P_{\text{grid}}(t)$$

The constraints are as follows:

i. Power balance constraint

$$P_{\text{grid}} = P_{\text{aggregate}} - P_{\text{battery}}$$

$$P_{\text{aggregate}} = P_{\text{load}} - P_{\text{PV}}$$

where P_{grid} is the power input to the micro-grid from the main grid, $P_{\text{aggregate}}$ is the net load power, P_{load} is the load power, P_{PV} is the output of photovoltaic power generation, P_{battery} is the output of storage system.

ii. Energy storage power constraint

$$P_{\text{battery\_min}} \le P_{\text{battery}} \le P_{\text{battery\_max}}$$

iii. Self-balance rate constraint

The grid-connected micro-grid is connected to the large grid and the large grid can provide some power support. In a certain period, the ratio of meeting the load demand through grid-connected micro-grid relying on their own distributed power is defined as the self-balancing rate, as shown in the following formula:

$$R_{\text{self}} = \frac{E_{\text{self}}}{E_{\text{total}}} \times 100\% = \left(1 - \frac{E_{\text{grid-in}}}{E_{\text{total}}}\right) \times 100\%$$

where R_{self} is the self-balancing rate, E_{self} is the load energy consumption that the grid-connected micro-grid can satisfy itself, E_{total} is the total load demand, $E_{\text{grid-in}}$ is the load power consumption that is satisfied by the large power grid, i.e. purchase electricity.

iv. Self-sufficient rate constraint

The distributed power supply of grid connected micro-grid cannot only supply the power to the load, but also can send electricity to the large power grid in the case of excess power generation capacity. In a certain period, the proportion of distributed power generation for load demand is defined as the self-sufficient rate, as shown in the following formula:

$$R_{\text{suff}} = \frac{E_{\text{self}}}{E_{\text{DG}}} \times 100\%$$

where R_{suff} is the self-sufficient rate, E_{self} is the load power consumption that the grid-connected micro-grid can meet, E_{DG} is the total distributed generation of grid-connected micro-grid.

v. Self-smoothing rate constraint

The self-smoothing rate is also known as tie line power volatility.

$$\delta_{\text{line}} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(P_{\text{line},i} - \overline{P_{\text{line}}})^2}$$

where δ_{line} is the self-smoothing rate, $P_{\text{line},i}$ is the power of tie line at time I, $\overline{P_{\text{line}}}$ is the average power of tie line during 24 h.

In order to ensure the reliable and economical operation of the micro-grid, the real-time energy management strategy of micro-grid is determined as follows:

i. When the net load $P_{\text{aggregate}}(t) = P_{\text{load}}(t) - P_{\text{PV}}(t) < 0$, photovoltaic power is charged to the battery under the condition of satisfying the load power. At this time, the load level is low and the electricity price is low, so the battery stores low-cost electricity.

a. The battery pack is charged but not full.

$$P_{\text{bat}}(t) = |P_{\text{aggregate}}(t)|$$

Battery state of charge is updated.

$$\text{SOC}(t+1) = \text{SOC}(t)(1-\sigma) + P_{\text{bat}}(t)/E_{\text{bat}}$$

where E_{bat} is the storage capacity of the battery, σ is the self-discharge rate of the battery per hour.

b. If the battery pack is full, there is still surplus power generation and the power will transmit to the main network.

$$P_{\text{grid}}(t) = -|P_{\text{aggregate}}(t)| + P_{\text{chmax}}$$

where P_{chmax} is the maximum battery charging power.

ii. When the net load $P_{\text{aggregate}}(t) = P_{\text{load}}(t) - P_{\text{PV}}(t) = 0$, battery state of charge i

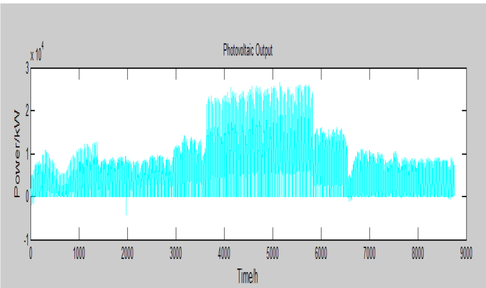

Fig. 3 *Solar panel output*

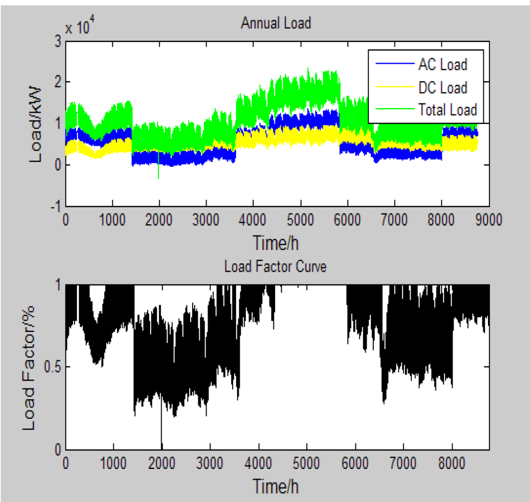

Fig. 4 *Year load data*

$$\text{SOC}(t+1) = \text{SOC}(t)(1-\sigma)$$

iii. When the net load $P_{\text{aggregate}}(t) = P_{\text{load}}(t) - P_{\text{PV}}(t) > 0$, the first choice is to use battery storage of low-cost electricity supply shortfall.

a. If the low price of the storage battery is sufficient, the charge state of the battery group is

$$P_{\text{bat}}(t) = -(P_{\text{load}}(t) - P_{\text{PV}}(t))$$

$$\text{SOC}(t+1) = SOC(t)(1-\sigma) + P_{\text{bat}}(t)/E_{\text{bat}}$$

b. If the battery storage of low-cost electricity is not enough to meet the supply shortfall, we need to buy electricity from main network, and purchase electricity is

$$P_{\text{grid}}(t) = P_{\text{aggregate}}(t) - P_{\text{dhmax}}$$

where P_{dhmax} is the maximum battery discharging power.

5 Case study

5.1 Basic data

Taking the industrial park shown in Fig. 1 as an example, it is an AC/DC hybrid system that includes three voltage levels of 10 kV AC, 380 V AC, and ±375 V DC. The system includes photovoltaic, energy storage device, and industrial AC and DC loads. Through multi-port PETs, it can realise the access and complementary coordination of sources and loads, and realise the reliable access of PV and the economic power supply of industrial loads. Take the PV output data and year load data of the industrial park as the input data for calculation, as shown in the curve of Figs 3 and 4.

The self-discharge rate per hour of the battery is 0.01%. The initial state of charge SOC (0) = 0.4, $\text{SOC}_{\max} = 0.9$, $\text{SOC}_{\min} = 0.2$. The maximum exchange power between the micro-grid and the main grid is 500 kW. Table 2 shows the price of electricity at different periods.

PSO algorithm is used for double-layer optimisation. The initial particle number is 20 and the number of iteration is 100. After debugging the optimisation programme, the learning factor is $c1 = c2 = 2$, and the inertia weight coefficient is 0.9 and 0.4 in order to ensure that particles have faster learning speed and convergence speed.

5.2 Optimisation results analysis

i. Take 1 day as the research period, the photovoltaic and load curves are shown as in Fig. 5.

The curve of energy purchase and state of charge obtained by capacity optimisation in the inner layer is shown in Fig. 6.

Combined with Figs. 5 and 6 analysis, we can get

a. 1:00–12:00, the net load is >0, i.e. the PV power generation does not meet the load power supply. At this time, the electricity shortage is supplemented by batteries and power grids at the same time due to the low electricity price;

b. 13:00–17:00, the net load is <0, i.e. photovoltaic power supply to meet the load, the remaining charge to the battery, leaving some reserve, and then the rest input to the main grid. At this time is also the highest price of electricity during the period, effectively reducing the cost of purchasing electricity;

c. c. 18:00–24:00, although the net load is >0, its value is not large. It is mainly compensated by the power supply of grid to save the stored energy and spare enough for compensating for the power shortage on the next day.

Capacity configuration results are shown in Table 3.

The cost of electricity purchase optimisation curve is shown in Fig. 7.

Table 2 Time-of-use electricity price

Time, h	1:00–8:00	9:00–12:00	13:00–18:00	19:00–21:00	22:00–24:00
Price, $, kWh	0.033	0.068	0.171	0.068	0.033

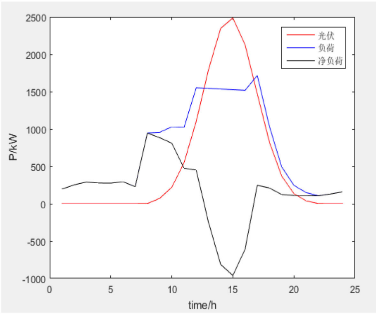

Fig. 5 *Typical daily PV and load curves*

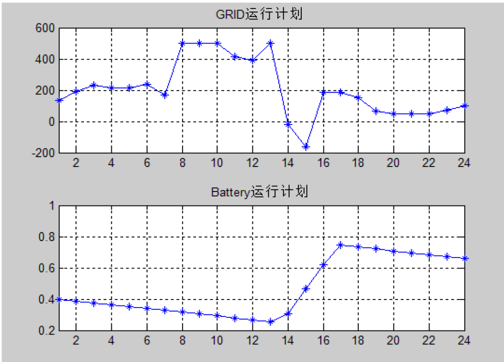

Fig. 6 *Grid power (kW) and SOC*

Table 3 Capacity configuration results

	Type	Capacity	Number
Battery	VRB-50	50 kWh	21

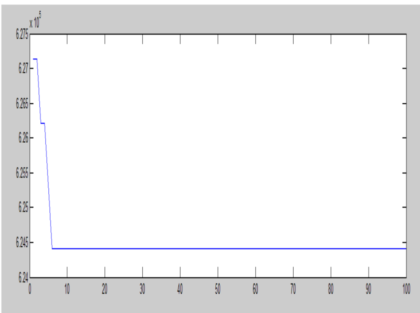

Fig. 7 *The cost of electricity purchase optimisation curve*

Take 1 year as the research cycle, Figs. 8 and 9 show the change of power from grid and battery.

ii. The optimal placement of energy storage is ±375 V DC port of PET.

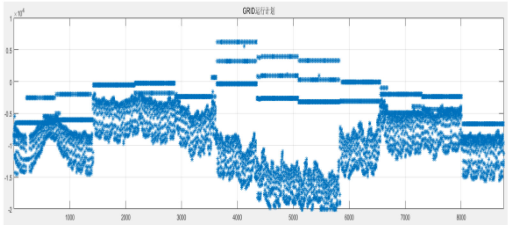

Fig. 8 *Grid power (kW)*

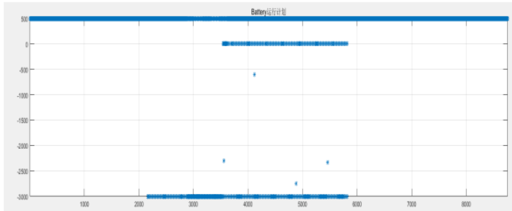

Fig. 9 *Battery power (kW)*

6 Conclusion

In the background of AC/DC hybrid distributed renewable energy is becoming more and more popular, a double-layer optimisation scheme of energy storage based on PET is proposed. The inner layer realises location selection, the outer layer determines the optimal capacity, and the inner and outer layer is connected by the power of photovoltaic and energy storage. It fully considers the power flow mode and port loss of PET, reduces the whole network loss, and improves the net profit of grid operation.

7 Acknowledgment

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