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ORIGINAL ARTICLE

Research on Economic Evaluation Method of Energy Storage System Connected to Distribution Network

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Abstract

The distribution network directly provides power to power users, customer service quality and improve the economy of power system. At the same time, the large-scale integration of renewable energy with the continuous growth of distribution network load, the peak valley effect of power grid load is gradually widening; at the same time, the large-scale integration of renewable energy with strong randomness and volatility has aggravated the peak shaving problem of the power system. After the energy storage system is connected to the distribution network, it can not only reduce the investment cost, improve the voltage quality, reduce the system network loss, but also provide a way to make the system more reliable and reduce the load fluctuation. The access location, capacity and operation scheduling strategy of energy storage system will affect the reliability of distribution network, and also the access location, capacity and operation scheduling strategy of energy storage system will affect the reliability of distribution network, and also greatly affect the economy of the overall operation of the system. Therefore, this paper proposes an evaluation method of energy storage system access to distribution network and studies the collaborative planning.

Keyworks: distribution network, economy, energy storage system, reliability.

Introduction

Electricity is the easiest form of energy to control and realize in production, transformation and transmission, and it has the advantages of high efficiency, convenience and cleanliness.

In recent years, on the one hand, the regional distribution networks are increasingly loaded, and the difference between peak and trough power loads is getting bigger and bigger, so many areas must pull the switch to meet the power requirements of important users; on the other hand, in order to meet the peak load often to update the grid equipment, which seriously affects the operating economy of the power system. In addition, as the large-scale random and volatile new energy sources are incorporated into the grid, the problem of power system peaking becomes more and more significant, which also brings a lot of difficulties for the power dispatching department. Taking into account the reliability of power supply, but the daily duration of load peaks is very short, and the utilization rate of power supply and transmission and distribution equipment decreases to accommodate short-time load peaks[1][2].

The distribution network adopts energy storage battery as the peaking power source, i.e., storing electricity during the night load valley hours and discharging it during the day load peak hours, using the time and space transfer of electricity and load to obtain peak and valley tariff difference to obtain income and improve the economics of the distribution network system[3].

The literature proposes a planning method for the location and capacity of energy storage in the distribution network considering the reliability and economy of energy storage system access to the grid. The literature proposes an optimization scheme combining DESS capacity allocation and orderly deployment, including the upper-level model and the lower-level model[4][5][6].

The literature provides a comprehensive quantitative assessment of the economics of energy storage applications in distribution grids, taking into account the costs and benefits of energy storage over its entire life cycle, and establishes a comprehensive assessment method for the economics of energy storage[7].

Based on the Markov bimodal model, a distributed energy multi-state model considering the reliability of equipment is established, [8][9]which includes PV, wind and storage systems. A method is proposed to evaluate the reliability of the distribution network power supply and is tested by simulation with a test system. The paper proposes a new multi-state modeling and reliability analysis method for distribution networks considering the multiple functions and flexible operation of energy storage and its impact on system reliability, and establishes an active distribution network reliability analysis method based on sequential Monte Carlo simulation[10] [11].

II. Energy Storage Technology and its Applications

In recent years, with the continuous innovation of energy storage materials and their related manufacturing processes, coupled with the increasingly important role played by energy storage technology in various fields, more and more advanced energy storage technologies have emerged. One of the emerging energy storage methods is distributed energy storage system. Regardless of the energy storage method of distributed energy storage, the fundamental energy conversion method remains the same, and the relevant principles are shown in Fig .1.

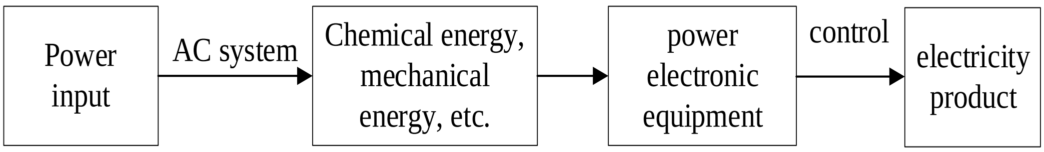

Figure 1 Principle diagram of energy conversion of energy storage device

A. Energy Storage Technology Development Status

Globally, energy storage technology is being actively promoted and planned to meet the ever-changing market demand. With the rapid rise of new energy generation and the continuous maturity of power electronics technology, energy storage system has become one of the current hot spots of research and development in the energy field, and will become an indispensable pillar for the future development of power system. The current energy storage technology types are more, a variety of energy storage technology development status there are large differences.

1) Pumped storage is one of the earliest researched and developed technologies in the world, and China's pumped storage has been developed to a world-class level. The excess electricity from the grid is used to drive the motor and pump the water from the downstream reservoir upstream to store it [12].

2) Compressed air energy storage: By compressing and releasing air, the conversion of energy in the space-time dimension is realized. Compressed air energy storage technology has good economy and environmental protection. By using compressed air energy storage technology, not only can we reduce investment costs, but also effectively save fuel, thus effectively reducing the emission of carbon and other pollutants.

In summary, pumped storage will remain the preferred choice for energy storage in high-capacity power systems in the future, and this trend will continue; as time goes by, more and more energy storage methods will be used in the form of compressed air, and this method will continue to develop and improve; in addition, the use of seawater or groundwater as thermal energy storage also has broad prospects. Molten salt thermal storage technology, as an innovative way to utilize solar energy, provides a brand-new way for the efficient use of energy. In addition, the application of energy storage systems is very promising because of their inherent advantages such as good economy and reliability.

B. Tracking planned power output

In order to meet the demand for electricity in the distribution network, the energy storage system can adjust the output state of the new energy source in order to make the new energy generation closer to the latest forecast[13]. The tracking plan output diagram is shown in Fig. 2.

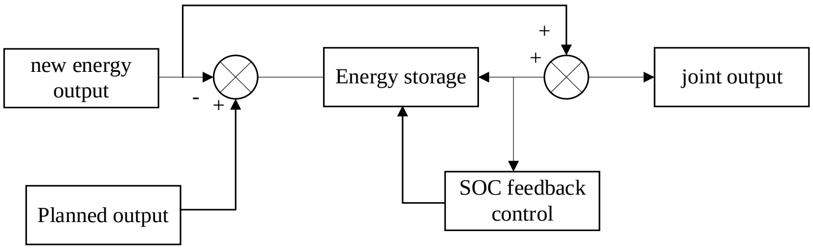

Figure 2 Tracking plan output diagram.

If the energy storage system handles the planned output curve before the day in a fully compensated way, it may cause the storage system to stop operation after reaching the SOC limit, because the SOC of the storage system will be limited to a certain extent; at the same time, if no corresponding measures are taken to control the start and stop of the current unit, the power system will lose its inherent characteristics and even collapse. It is not possible to track the power plan in real time, and it is not possible to effectively suppress the voltage fluctuation in the grid and other problems.

III. Economic Evaluation of Energy Storage System Connected to the Distribution Network

The intermittent and fluctuating nature of energy storage batteries makes grid planning difficult. Therefore, the focus of this chapter is to use the energy storage system to cut the peaks and fill the valleys of the connected distribution network in order to establish the economic efficiency assessment index of the energy storage system.

A. Life estimation model of energy storage battery

The concept of energy storage battery life is generally vague, people generally believe that the storage battery can only store electricity to meet 75% of the capacity requirements when the battery is just used up, then it should be stopped. Many reasons can have an impact on battery. The energy storage battery life calculation model is shown in (1).

$$B_L = \frac{1}{\sum_{i=0}^{N_0} M_{i.R}} \tag{1}$$

where $M_{i.R}$ is the life loss of the battery corresponding to the ith cycle of charging and discharging at the depth of discharge *R*.

For the calculation of battery life loss under frequent charge and discharge, the equivalent charge and discharge coefficient of the energy storage battery is also defined considering the depth of each charge and discharge, as shown in (2) 14.

$$\alpha = \frac{N_i}{N_0} \tag{2}$$

where N_i is the maximum number of cycles when the ith charge and discharge is converted to the full full down.

Then the M_i calculation formula is shown in (3).

$$M_i = \frac{\alpha}{N_0} \tag{3}$$

Charge and discharge depth *R*, the number of battery cycles can be quantified by (4).

$$N_\alpha = \alpha_1 + \alpha_2 e^{-\alpha_3 R} + \alpha_4 e^{-\alpha_5 R} \tag{4}$$

Where α_1, α_2, α_3, α_4, α_5 is a set of constants, obtained by regression simulation of battery life test data14.

B. Cost calculation model considering the life of energy storage batteries

Energy storage batteries are rarely used in the main network system due to capacity and volume constraints, and are even rare when installed in distribution networks. Energy storage battery structure is more complex, usually as in Fig. 3, the composition of the structure of the battery pack, rectifier and inverter, battery pack management system and protection control system.

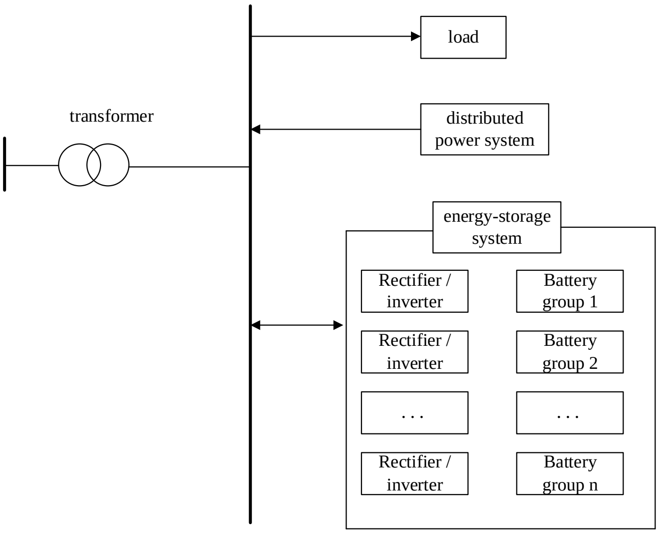

Figure 3. Schematic diagram of the electrical structure of the energy storage system.

The primary investment cost includes three parts: the investment cost of power conversion equipment, the investment cost of battery management system, and the investment cost of related auxiliary equipment. Its calculation formula is shown in (5) 16.

$$C_1 = k_e E_N + k_p p_N + k_f P_N \tag{5}$$

Where, C_1 is the primary investment cost ; K_e is the unit capacity cost of the battery pack and its management system;k_p is the unit power cost of the power conversion system;k_f is the unit power cost of the auxiliary equipment;P_N is the rated power of the energy storage battery;E_N is the rated capacity of the energy storage battery.

The O&M cost of the battery storage system is expressed in (6) over its whole life cycle.

$$C_2 = \sum_{i=1}^{T} k_{ri} P_{Ni} \tag{6}$$

where C_2 is the operation and maintenance cost of the energy storage battery;k_{ri} is the O&M cost per unit capacity of the energy storage battery in the ith year;P_{Ni} is the battery capacity of the energy storage battery to be maintained in year i;T is the operation time of the energy storage plant, which is converted into years by the number of cycle life of the battery.

Connecting the energy storage system to the distribution network will bring multiple benefits, which will be analyzed in the following detailed modeling.

Connecting the energy storage system to the distribution network can realize the differential regulation of peak and valley tariffs, thus bringing considerable economic benefits. As the economy develops and technology advances, customers' requirements for power supply reliability are getting higher and higher, and grid companies must provide reliable and high-quality electricity. As an emerging electricity market model, the proposed time-sharing tariff has attracted widespread social attention. The energy storage system is charged when the load is low and discharged when the load is peak, and this process can take full advantage of this policy to achieve profitability, and its revenue expression can be used in (7).

$$B_{S1} = \sum_{i=1}^{T} \left(\rho_{ufi} - \rho_{ugi} \right) \Delta Q_i \tag{7}$$

where B_{S1} is the economic gain from the energy storage system connected to the distribution grid through the difference between peak and valley tariffs;ΔQ_i is the amount of electricity that is used for peak and valley reduction through the energy storage system in year i;ρ_{ufi} is the peak and valley time-sharing tariff implemented on the grid side in year i.

During the operation of the distribution network, due to the large peak-to-valley difference on the load side, it will have a negative impact on the primary and secondary equipment, so the distribution network must be upgraded and expanded. Due to the scale and complexity of the distribution network itself, and the limitations of geographic location, terrain conditions and historical reasons, there are many difficulties in the expansion of the distribution network.

Therefore, during peak load periods, those areas where the rated capacity of the grid is often exceeded, energy storage devices can be used, and the expression for the benefits achieved on the grid side due to reduced capacity upgrades and expansions of distribution equipment is shown in (8).

$$B_{s2} = \sum_{i=1}^{T} A_{si} \Delta Q_{si} \tag{8}$$

where B_{s2} is the benefit obtained from the reduced distribution equipment capacity upgrade and expansion after the energy storage battery is connected to the distribution grid;A_{si} is the capacity upgrade and expansion capacity cost per unit of distribution equipment capacity in year *i*.At the same time, in the context of the energy Internet, the use of the demand side of electricity to provide services to customers is also a new direction.

The expression of the state special fund incentive benefit obtained by the distribution grid side is shown in (9).

$$B_{s3} = \sum_{i=1}^{T} k_{si} \cdot \Delta P_i \tag{9}$$

where B_{s3} is the national special fund incentive revenue obtained by the energy storage battery installed on the distribution network side;k_{si} is the government subsidy for the ith year when the energy storage battery cuts unit peak load;ΔP_i is the power value of the system cut off by the energy storage plant in the ith year.

In order to meet the equation requirements of grid dispatch, an independently operating grid must ensure that its power consumption is equal to its power generation. If there is a peak in electricity consumption in a given area on a given day, then there will be a large amount of excess electricity in that area. Therefore, power plants must be built to ensure that their capacity can meet the demand for electricity at peak load levels, and therefore must be built with significantly higher capacity than the average load level.

Therefore, the connection of the energy storage system to the distribution network will bring benefits to the generation side, including the benefits from the reduction of unit equipment capacity upgrade and expansion, and the benefits from the reduction of frequent unit start stop peaking, as shown in the expressions in (10) and (11).

$$B_{G1} = \sum_{i=1}^{T} A_{Gi} \Delta Q_i \tag{10}$$

$$B_{G2} = \sum_{i=1}^{T} \lambda_i C_i \tag{11}$$

where B_{G1} is the capacity gain due to reduced unit equipment capacity upgrade and expansion after installation of energy storage batteries;A_{Gi} is the cost per unit capacity of the expanded generation equipment;ΔQ_i is the upgraded unit capacity;B_{G2} is the benefit from the installation of energy storage batteries due to the reduction of frequent start-up and stop-up peaking of the unit;λ_i for the cost per unit mass of combustion;C_i for the fuel required to start and stop the unit once.

At present, with the continuous development and application of peaking measures, traditional thermal power plants take up most of the peaking tasks, which not only consumes a lot of energy, but also causes serious pollution to the environment. The evolution and use of energy storage devices have played an irreplaceable role in several fields such as environmental protection and energy conservation. Its mathematical model can be expressed by (12).

$$S_{enviroment} = (\sum_{i=1}^{n} R_{metali}\rho_{metali} - R_{recyclei})\delta_{energyi}E_i + \left(\sum_{1}^{365}\sum_{i=1}^{24} P_i\right)R_{TP} \tag{12}$$

where $S_{environment}$ is the environmental benefit of the energy storage system, which consists of two components. The recovery benefit obtained by the energy storage system at the end of its operational life is the first term of the equation; the coal saving benefit brought by the energy storage system replacing thermal power peaking is the second term of the equation;[16]

R_{metali} is the price of metal i;ρ_{metali} is the content of metal i in a unit weight of energy storage battery;$R_{recyclei}$ is the productive expenditure required to dispose of a unit weight of waste battery;$\delta_{energyi}$ is the energy-to-weight ratio of the energy storage system;R_{TP} is the cost per unit of power supply for conventional thermal power units.

C. Objective function to maximize the total benefit of the energy storage system

After the energy storage system is connected to the distribution network, the benefits obtained by the energy storage system minus the primary investment cost and operation and maintenance cost of the energy storage battery are the objective function of the maximum total benefit (13):

$$\max f_B = B_{S1} + B_{S2} + B_{G1} + B_{G2} + S_{enviroment} - C_1 - C_2 \quad (13)$$

D. Constraint conditions

1) Energy storage power constraint

$$P_{store\_\min} \le P_{store} \le P_{store\_\max} \quad (14)$$

Where, P_{store_min} and P_{store_max} are the lower and upper limits of energy storage system power, respectively.

2) Charge state constraint

$$SOC_x^{\min} \le SOC_{x,t} \le SOC_x^{\max} \quad (15)$$

where, SOC_x^{min} and SOC_x^{max} are the minimum and maximum charge states of the energy storage system, respectively.

IV. Example Analysis

For the distribution network of a certain region, we will select typical daily load data for in-depth analysis, and draw a typical daily load curve of the region according to the load situation of each time period, which is shown in Fig. 4.

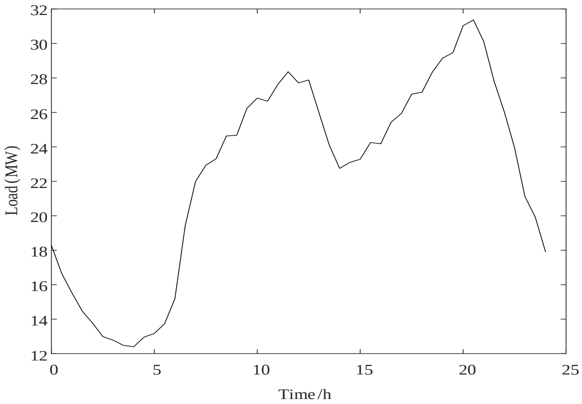

Figure 4 Typical daily load curve of a region

According to Fig. 4, the load in the region shows obvious fluctuation characteristics. Among them, the daily average load curve shows a bimodal distribution, i.e., it is in a higher load state during the daytime, while it is in a low load state at night. The peak load value is 31.36 MW, and the low load value is 12.41 MW, with a peak-to-valley difference of about 60.43%; the difference between the peak load and the low load season is large. And the load trough is usually in the early morning, about 23:30 to 6:00, and the small peak of load is around 11:00 in the morning, while the peak of load is around 20:00 at night.

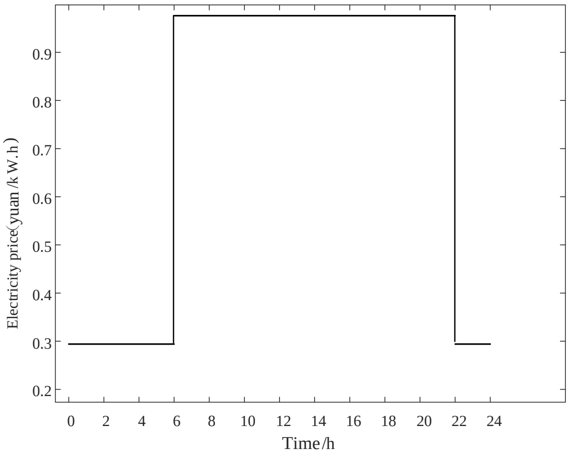

Figure 5 Peak-to-valley tariff of a region

After consulting with relevant departments, we learned that the electricity price in this area is 0.261 CNY/kW-h at low load (0:00~6:00) and 0.812 CNY/kW-h at peak load (6:00~22:00), but there is a significant difference in the peak and valley electricity prices. The comparative analysis shows that the use of energy storage system can effectively improve the quality of local power supply, thus reducing the customer's electricity expenditure and grid operation cost. Energy storage batteries are considered to be connected to this distribution network to achieve peaking of grid loads. In this paper, we calculate the economic parameters of energy storage batteries at different capacities and establish a mathematical model, and finally propose a corresponding economic dispatching scheme based on the calculation results. At the same time, considering the cost of the energy storage battery and the user's income, the mathematical model of the distribution system planning with energy storage battery is established with the economy as the main index, and the optimal solution is solved by genetic algorithm. Table I shows the settings of the relevant parameters in the specific economy evaluation model k_{si}.

Table 1 Parameter Settings Of The Economy Evaluation Model

Parameter	Value taken
ρ_{ugi}	0.261 CNY/kW-h
ρ_{ufi}	0.812 CNY/kW-h
k_{si}	50,000 CNY/MW-h
A_{Gi}	21000000 CNY/MW-h
λ_i	70,000 CNY/MW-h
A_{si}	600,000 CNY/MW-h
k_e	3,500,000 CNY/MW-h
k_f	1,200,000 CNY/MW-h
k_p	30000000 CNY/MW-h
k_{ri}	500000 CNY/MW-h
k_{Ni}	22,000,000 CNY/t
R_{TP}	330000 CNY/MW-h
$R_{recyclei}$	31200000 CNY/MW-h
$\delta_{energyi}$	0.046

The relevant variables of the economic evaluation model in this section are set according to the values in Table I, and the objective function of the optimized economy is shown in (13), and the constraints are shown in (14) and (15), and are optimized according to the rated charging and discharging power and rated capacity of the energy storage battery. The optimal solution is obtained by solving the mathematical model established based on the results of the above analysis, i.e., the economic effect is maximized by changing the parameters. Based on the final simulation P_N optimization results, it is concluded that the optimal E_N power of the energy storage battery is 1.56 MW and the optimal capacity is 13.16 MW-h. In this case, the energy storage battery can gain 5,056,900 CNY per year, which is relative to the initial investment 50.74 million CNY, with an average return of 9.97% per year, and the cost is expected to be recovered in the next 10 years.

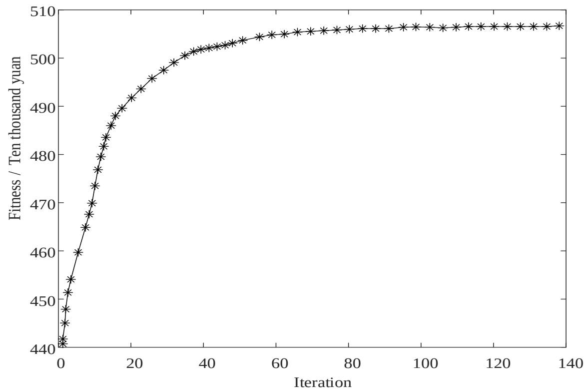

Figure 6 Optimization results of the genetic algorithm

In view of the low storage and high generation characteristics of the storage battery, the load trough in the area has been boosted to 15.72 MW, while the peak generator output has been cut to 28.15 MW. In order to complete the charging and discharging cycle, the storage battery needs to consume 1681 kW power, which is equal to 4100 kW-h capacity. During the whole process, the system is always in a stable state. After adding the energy storage device, the peak-to-valley difference is 44.15%, indicating that the energy storage device has a significant peak-shaving and valley-filling effect.

Fig. 7 presents the trend of SOC (state of charge) of the energy storage battery. Under different charging and discharging conditions, the energy storage battery can maintain normal working conditions and meet the design requirements. And the daily variation range of SOC of energy storage battery does not exceed 40%, there is no over-charging or over-discharging, which meets the requirements of safe use of energy storage battery and rational use of resources under the condition of high battery utilization.

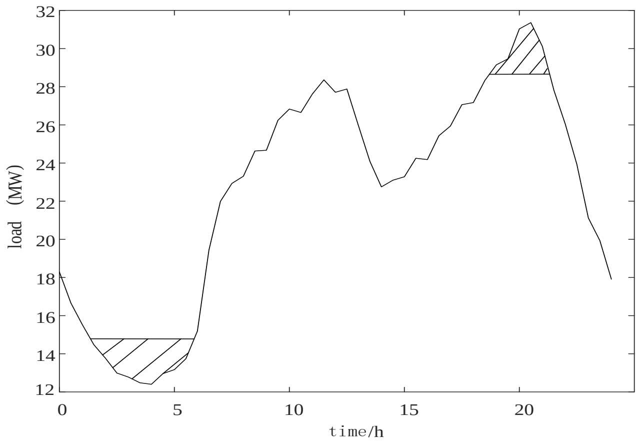

Figure 7 Synthetic output curve of energy storage battery after participating in peak regulation

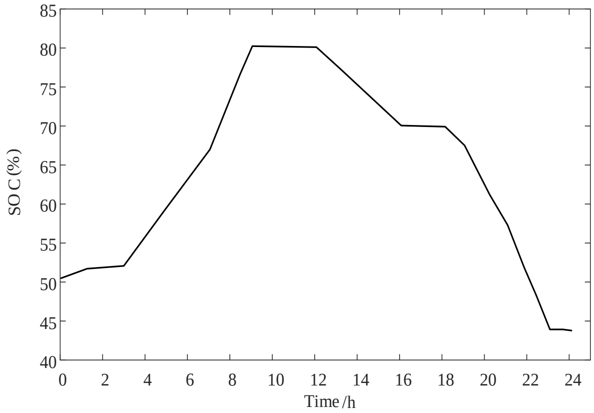

Figure 8 Trend of SOC change of energy storage battery.

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