

Capacity Configuration of Energy Storage Systems for Echelon Utilization Based on Accelerated Life Test in Microgrids

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Abstract—Retired power battery construction energy storage systems (ESSs) for echelon utilization can not only extend the remaining capacity value of the battery, and decrease environmental pollution, but also reduce the initial cost of energy storage systems. In this paper, an ESS constructed of retired power batteries for echelon utilization in microgrids (MGs) is considered. Firstly, considering the influence of different discharge depths on the battery life cycle, the correlation equation between the state of charge (SOC) and the state of health (SOH) is established. Secondly, the accelerated life test method, based on the inverse power law coefficient equation, is proposed, and it is used to evaluate the reliability of the ESS. Finally, according to the SOC characteristics, the dynamic security margin of the ESS is established. The life cycle cost, supply-demand balance and ESS balanced control are comprehensively considered, and the location and capacity of energy storage in MGs are determined. It is simulated using the IEEE-RTS 24 node system; the results show that the investment cost of the ESS is reduced and the operational life is prolonged.

Index Terms—ESS, echelon utilization, accelerated life test, balanced control, capacity configuration.

I. INTRODUCTION

IN recent years, with the rapid development of the electric vehicle industry, the production of vehicle power batteries are gradually increasing, which leads to a sharp rise in retired power batteries [1], [2]. Therefore, the echelon utilization technology for retired power batteries is being developed throughout the world, allowing for environment-friendly and resource-saving industrial structures to develop rapidly [3], [4].

With the market demand for echelon utilization of retired power battery expanding, the research on state evaluation and stable operations of ESSs is becoming a hot topic [5]. Currently, researchers at home and abroad have launched a

series of studies on this issue. A model of cell attenuation is proposed. The remaining capacity of the battery is converted into the corresponding cycle life characteristics, and the synchronous prediction method is used to predict the state of the battery [6]–[8]. The SOH characteristics of batteries are evaluated by the method of variable analysis [9], [10]. Considering the influence of the internal parameters on their health state, the SOH of a battery is evaluated based on the particle swarm optimization algorithm in [11]–[13]. The health parameters of the LiFePO₄ power battery are extracted by the nonlinear least square method, and the capacity of the battery is detected in [14], [15]. These studies focused on the effect of internal parameters on battery health, but the correlation characteristics of capacity, and the SOC and SOH are not established to support the reliability evaluation.

If the capacity of the power battery is between 70% and 80% of the initial value, it needs to be decommissioned [16]–[19]. It is primarily used to stabilize the fluctuation of distributed energy power output, and realize peak cutting and valley filling for the power grid [20]. A large number of research and demonstration projects have been carried out at home and abroad, such as the research project of retired lithium batteries for echelon utilization carried out by National Renewable Energy Laboratory in China [21]. At the beginning of 2020, the first demonstration project of retired power batteries for echelon utilization in China was established, with a total capacity of 3 MWh [22].

When the retired battery is used in a power system, the primary problem to be solved is the capacity configuration of the ESS for echelon utilization [23]. Considering the life cycle cost of the ESS, the capacity allocation method of the ESS based on the variable life model is proposed in [24], [25]. Reference [26] proposes a double-layer capacity allocation decision-making model. Considering the initial investment cost and the penalty cost of the tie line, the optimal allocation of the ESS is carried out. The energy storage capacity allocation strategy based on DSM is proposed in [27]. According to the above analysis, there are few references about the capacity allocation method of the ESS when the retired power battery is used in echelon utilization. Meanwhile, the influence of the differences of SOH on the configuration is not considered in the configuration.

In view of the above problems, MGs are taken as the configuration object, and the power interaction between MGs is fully considered, which is more suitable for the echelon

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utilization of the ESS. A reliability analysis method based on the accelerated life test is presented in this paper, and the correlation characteristics of capacity, SOC and SOH is established. The dynamic safety margin of ESS charging and discharging is established. In addition, the life cycle cost of the ESS and the influences of balance control on the capacity configuration are fully considered, and the balance of supply and demand within the system is determined for location and capacity.

The contributions of the paper are summarized as follows:

1) The accelerated life test method of a battery based on the inverse power rate equation is proposed.

2) The correlation characteristics of capacity, SOC and SOH are established, the dynamic security margin of the ESS for echelon utilization is established, and the capacity of the MGs is configured.

The rest of this paper is organized as follows: Section II analyzes the reliability of the accelerated life test. Section III presents the location and configuration capacity of the ESS based on the dynamic security margin. Experimental verifications are presented in Section IV. Section V concludes the paper.

II. RELIABILITY ANALYSIS BASED ON ACCELERATED LIFE TEST

When the retired power battery construction ESS for echelon utilization is used in the power system, there are some problems in the initial capacity, SOC and SOH of the single battery. If the traditional estimation method is adopted, the time cost and investment cost increases. Therefore, in order to quickly and accurately estimate the parameters of the battery and evaluate the health status of the ESS, an accelerated life test is used. This method can improve the estimation efficiency without affecting the accuracy of the evaluation.

A. Establish Capacity, SOC and SOH Correlation Characteristics

The nonlinear characteristic is obtained in the process of battery charging and discharging. The equivalent circuit model of a single battery is established, as shown in Fig. 1 [28].

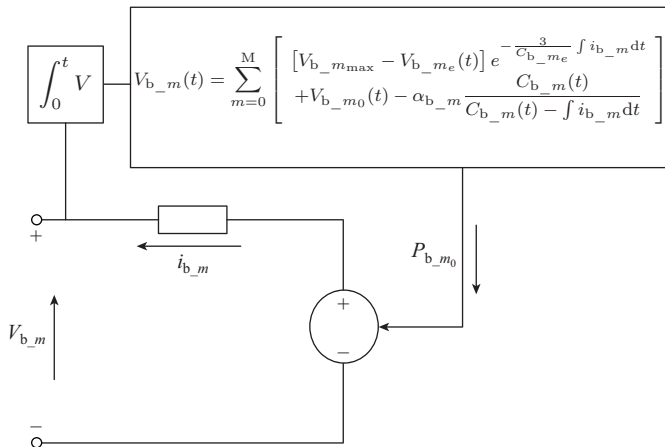


Fig. 1. Equivalent model of a single battery.

The relationship between voltage V_{b_m} and capacity C_{b_m} is,

$$V_{b_m}(t) = \sum_{m=1}^M \left[[V_{b_m_{\max}} - V_{b_m_e}(t)] e^{-\frac{3}{C_{b_m_e}} \int i_{b_m} dt} + V_{b_m_0}(t) - \alpha_{b_m} \frac{C_{b_m}(t)}{C_{b_m}(t) - \int i_{b_m} dt} \right] \quad (1)$$

where m is the serial number of single battery, M is the number of single batteries in the ESS, $V_{b_m_{\max}}$ is the full charge voltage amplitude/V, $V_{b_m_e}(t)$ is the limit value of exponential region voltage/V, $C_{b_m_e}$ is the index area capacity/Ah, $i_{b_m}(t)$ is the current value of charging and discharging/A, $V_{b_m_0}(t)$ is the initial voltage value/V, α_{b_m} is the amplitude within the index region of the single battery.

The SOC $_{b_m}(t)$ of the battery is,

$$\text{SOC}_{b_m}(t) = \sum_{m=1}^M \frac{3600C_{b_m}(t) - \int i_{b_m} dt}{3600C_{b_m}(t)} \times 100\% \quad (2)$$

The power output of the ESS system has a certain correlation with SOC, which is expressed as the life decay function corresponding to the two charges and discharges of ESS, as shown in formula (3) [29].

$$\text{SOC}_{b_m}(t+1) - \text{SOC}_{b_m}(t) = \frac{\int_t^{t+1} P_{b_m}(t) dt}{C_{b_0_m}} \quad (3)$$

where $P_{b_m}(t)$ is the real-time output power/kW, $C_{b_0_m}$ is the initial nominal capacity/kWh.

The mathematical model of ESS life attenuation at time t is,

$$\begin{aligned} \Delta\beta_{b_m}(t) &= \beta_{b_m}(t) - \beta_{b_m}(t-1) \\ &= \frac{\text{SOC}_{b_m}(t)}{\text{SOC}_{b_m}^{\max}} \times \frac{l_{\alpha b_m}(t)}{P_{b_m}(t) \cdot \text{SOC}_{b_m}(t-1)} \end{aligned} \quad (4)$$

where $l_{\alpha b_m}(t)$ is the life attenuation value of the ESS/Times, $\text{SOC}_{b_m}^{\max}$ is the maximum SOC value, $l_{\alpha b_m}(t)$ is the charge and discharge of the response factor, $\beta_{b_m}(t)$ is the degree of attenuation.

Considering the decay of life in the charge and discharge process, the power function fitting method is used to fit the experimental data of the ESS, and the corresponding relationship between the charge and discharge depth and life is obtained [30]. At the different depth D_m , the life L_{D_m} is,

$$L_{D_m} = \frac{1}{\sum_{n=1}^{n=N_{D_n}} \sum_{D_m=0}^{D_m=1} L_{\text{loss}_\delta, D_m}} = \sum_{n=1}^{n=N_{D_n}} \sum_{D_m=0}^{D_m=1} \frac{n_{D_m}}{\chi_\delta} \quad (5)$$

where N_{D_n} is the charge and discharge times, D_m is the charge and discharge depths, its value range is $[0, 1]$, $L_{\text{loss}_\delta, D_m}$ is the δ -th life loss of charge and discharge under depth D_m of the ESS/Times, χ_δ is the fitting parameter in the life estimation process.

The life $C_{b_m}(t)$ of the ESS is converted to the charge and discharge capacity in the whole life cycle, and χ_δ is converted

to the corresponding depth D_m . If formula (5) is brought into formula (6), the following can be obtained.

$$C_{b_m} = C_{b_0} \sum_{n=1}^{n=N_{D_n}} \sum_{D_m=0}^{D_m=1} \left(\frac{D_{m_\delta}}{D_{m_\varepsilon}} \right)^{\alpha_{m_\delta}} e^{\left(1 - \frac{D_{m_\delta}}{D_{m_\varepsilon}}\right)^{\alpha_{m_\varepsilon}}} \quad (6)$$

where C_{b_0} is the initial capacity of ESS/kWh, D_{m_δ} , D_{m_ε} are the depths of δ_{th} , ε_{th} charge and discharge, α_{m_δ} , α_{m_ε} are the fitting parameter χ_δ , χ_ε of current converted to D_{m_δ} , D_{m_ε} .

The relationship between charge and discharge depth and SOC is set to $D_m = 1 - SOC_{b_m}(t)$, and the quadratic function between SOC and capacity $C_{b_m}(t)$ is,

$$C_{b_m}(t) = \gamma_{b_m} SOC_{b_m}^2(t) + \eta_{b_m} SOC_{b_m}(t) + \kappa_{b_m} \quad (7)$$

where γ_{b_m} , η_{b_m} and κ_{b_m} are each coefficient, respectively. The constant depth of charge and discharge is D_m .

During the accelerated life test, the discharge rate is set to different values, and the SOH change characteristics are obtained. The correlation characteristics of capacity with SOC and SOH are as follows,

$$C_{b_m}(t) = C_{b_0_m} SOC_{b_m}(t) SOH_{b_m\delta}(t) \quad (8)$$

B. Accelerated Life Test Based on the Inverse Power Rate Equation

In order to effectively improve the regulation accuracy of the ESS in the distribution network, it is necessary to evaluate the service life of the ESS. Through the accelerated service life test, an inverse power rate model is proposed to evaluate the reliability of ESS [31]. The normal state of health is assessed. It is converted into the health characteristics under the accelerated charge and discharge ratio, and the expression is,

$$SOH_{b_m\delta} = SOH_{b_m} \frac{L_{D_{m_\delta}}}{L_{D_m}} \left(\ln \frac{D_{b_m\delta}}{D_{b_m}} \right)^{-h} \quad (9)$$

where $L_{D_{m_\delta}}$ is the δ_{th} life loss of the charge and discharge under depth $D_{b_m\delta}$.

The logarithm of formula (9) is established. Based on the variables under normal life conditions, the variables of the accelerated life test are converted according to the inverse power law equation. The relationship between the number of cycles of the ESS and SOH is shown in Fig. 2. It is linearized, and the property of introducing the expression of the inverse power law model is obtained, which is shown in Fig. 3.

According to Fig. 3, it can be seen that the given acceleration charge and discharge ratio is different, and the SOH characteristics obtained are different. The SOH characteristics under four different charge and discharge ratios are listed. When the limit value $D_{m_{max}}$ is given, the minimum value SOH_{min} of the health characteristic is obtained. When the given acceleration charge and discharge ratio is D_{m_δ} , the corresponding health characteristic is $SOH_{b_m\delta}$. A_m is the natural logarithm of life attenuation under different charge and discharge depths for D_m , and its value is constant.

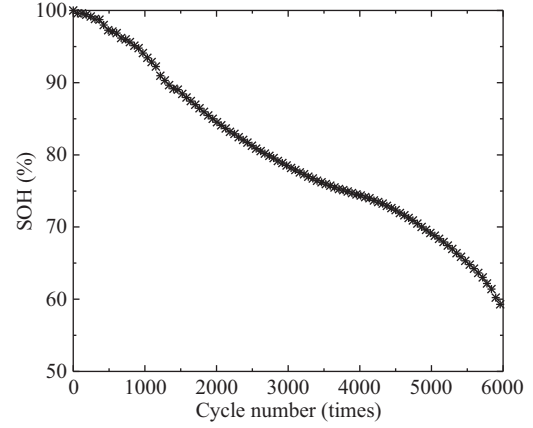


Fig. 2. Correlation between cycle number and SOH.

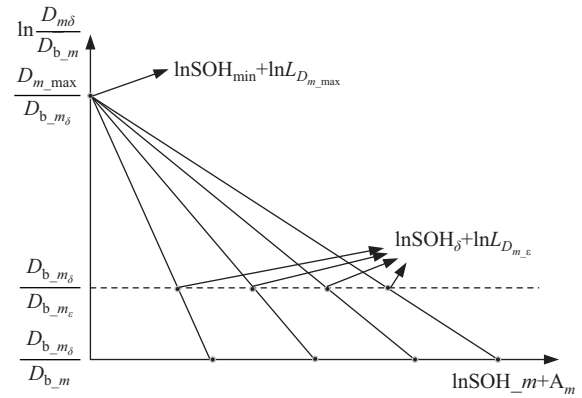


Fig. 3. SOH linearized output based on inverse power rate equation.

According to the points measured in the test, the minimum value SOH_{min} of the health characteristic is obtained. According to the points measured in the test, the formula for solving each parameter is obtained as follows,

$$\ln SOH_{b_m} = \ln \frac{SOH_{b_{min}} \times L_{D_m}}{SOH_{b_m} \times L_{D_{m_{max}}}} + h \left(\ln \frac{D_{b_m\delta}}{D_{m_{max}}} - \ln \frac{D_{b_m\delta}}{D_{b_m}} \right) \quad (10)$$

where $\ln \frac{D_{b_m\delta}}{D_{b_m}}$ is the known value under the corresponding charge and discharge ratio.

Under normal circumstances, the corresponding health characteristics are,

$$SOH_{b_m} = \frac{SOH_{b_{min}} \times L_{D_m}}{SOH_{b_m} \times L_{D_{m_{max}}}} \exp \left\{ h \left(\ln \frac{D_{b_m\delta}}{D_{m_{max}}} - \ln \frac{D_{b_m\delta}}{D_{b_m}} \right) \right\} \quad (11)$$

The health characteristics of the ESS under normal conditions are derived by the accelerated life test, which provides a theoretical basis for battery reliability analysis.

Based on the characteristics of scenario analysis, the reliability of ESS is analyzed, and then M batteries are selected. Under normal operational conditions, the SOH of ESS are set to $SOH_1, SOH_2, SOH_3, \dots, SOH_M$ respectively. According to the solutions of formulae (9)–(11), the logarithm

form $\ln \text{SOH}_1, \ln \text{SOH}_2, \ln \text{SOH}_3, \dots, \ln \text{SOH}_M$ are obtained, and then the average value of M batteries and the corresponding standard deviation s_{SOH_m} are calculated.

The accelerated life test is adopted, and the limited difference of error under the normal charge discharge ratio is $\mu_{\min}$. The reliability analysis of ESS should meet the following requirements,

$$\frac{s_{\text{SOH}_m} \times \ln \text{SOH}_{b-m\delta}}{\sqrt{M} \times \ln \text{SOH}_m} \leq \mu_{\min} \quad (12)$$

The SOH of ESS is predicted, and the error of prediction result is $[0, \mu_{\min}]$. The probability of each scene is obtained by discretizing it.

III. ESS CAPACITY ALLOCATION BASED ON DYNAMIC SAFETY MARGIN

A. Setting of ESS Dynamic Safety Margin Based on SOC

Because of the overcharge and overdischarge of the ESS in echelon utilization, it has a great influence on any loss. In the configuration of the ESS according to the SOC characteristics, the dynamic safety margin of ESS is first set to effectively improve the operational life. In the process of charging and discharging, a certain safety margin is reserved, and the fluctuation of output power of the MGs is more accurately and quickly restrained.

The ESS capacity of the MGs is configured, the limit power deviation $\Delta P_x(t)$ of system scheduling within one year is considered, and the ESS dynamic safety margin is established. The SOC range after echelon utilization is $[\min_SOC_{b-m}(t), \max_SOC_{b-m}(t)]$. In order to achieve power deviation in extreme cases, the SOC dynamic safety margin is established as $[\Delta_{\text{down_SOC}_{b-m}}(t), \Delta_{\text{up_SOC}_{b-m}}(t)] = [\text{down_SOC}_{b-m}(t) - \min_SOC_{b-m}(t), \max_SOC_{b-m}(t) - \text{up_SOC}_{b-m}(t)]$. In order to effectively ensure the balance of supply and demand and the stable operation of the power grid in daytime, a large safety margin is reserved during the peak period and normal period. The safety margin is smaller in the valley period at night. The schematic diagram is shown in Fig. 4 [32].

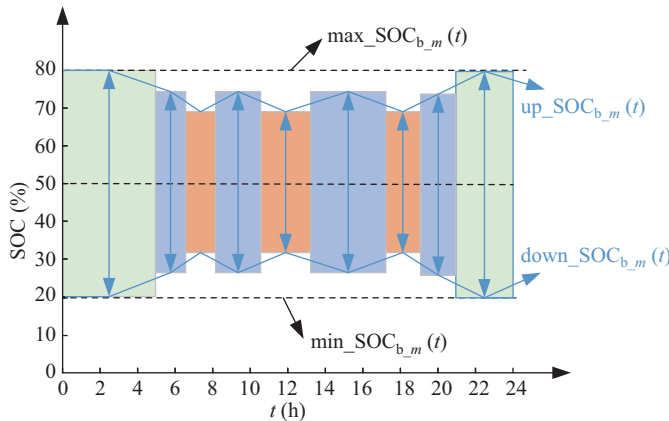


Fig. 4. Establish the safety margin of the SOC.

The limit dispatching deviation $\Delta P_x(t)$ within one year is converted according to the seasonal characteristics, and the

maximum power deviation $\max \psi \Delta P_x(t)$ corresponding to each day is obtained. The calculated safety margin of charge and discharge is,

$$\begin{cases} \Delta_{\text{down_SOC}_{b-m}}(t) = \frac{\max \psi \Delta P_x(t)}{\max N_{D_n} \times C_{b-m}(t)} \\ \Delta_{\text{up_SOC}_{b-m}}(t) = \frac{\max \psi \Delta P_x(t)}{\min N_{D_n} \times C_{b-m}(t)} \end{cases} \quad (13)$$

where ψ is the power conversion factor, $\max N_{D_n}$, $\min N_{D_n}$ are the extreme values of the charge and discharge times after echelon utilization.

B. Echelon Utilization ESS Configuration in MGs

During the echelon utilization of the ESS, the initial capacity is different. Therefore, the supply and demand balance of the MGs and the life cycle costs of the ESS are considered in the process of optimizing the configuration [33], [34]. The ESS equilibrium control based on the dynamic security margin is used as a constraint, and the location and capacity of the ESS can be reasonably installed. The basic structure of the MGs is shown in Fig. 5.

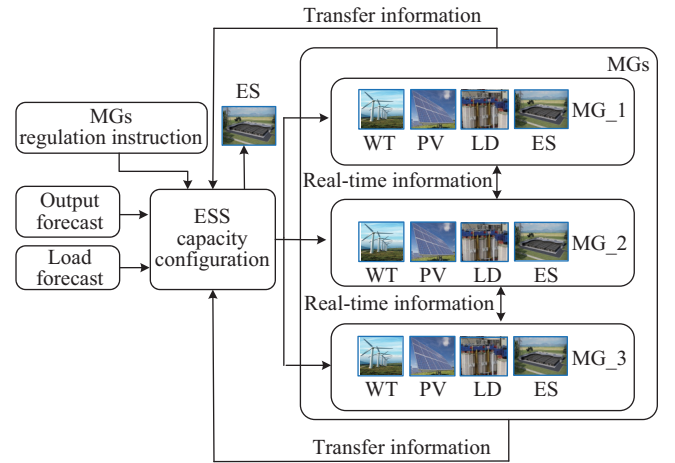


Fig. 5. Schematic diagram of the ESS access to the MGs.

1) Capacity Allocation Considering the Life Cycle Cost of the ESS

According to their capacity, and the SOC and SOH correlation characteristics established in the previous section, the main consideration is the life loss cost caused by ESS overcharge and overdischarge when the whole life cycle cost of the ESS is taken into account. When the capacity of the ESS is not enough, the phenomenon of wind turbine (WT) and photovoltaic (PV) abandonment leads to energy loss costs. The lack of ESS configuration results in the electricity purchasing cost from the power grid.

In the process of configuration, the influence of overcharge and overdischarge on the life loss is considered under different charging and discharging depths of the ESS. It is converted into a cost function, and the specific expression is,

$$f_{1-1} = \sum_{t=1}^T \sum_{m=1}^M \theta_{D_m} L_{D_m} \Delta C_{b_m}(t) \\ = \sum_{t=1}^T \sum_{m=1}^M \theta_{D_m} L_{D_m} |C_{D_m,\delta}(t) - C_{D_m,\varepsilon}(t-1)| \quad (14)$$

where T is the period corresponding to the time-of-use price/h, θ_{D_m} is the cost coefficient of charge discharge depth D_m , $\Delta C_{b_m}(t)$ is the capacity deviation value/kWh, $C_{D_m,\delta}(t)$, $C_{D_m,\varepsilon}(t-1)$ are the capacity values at different times and charge discharge depth/kWh.

If the ESS initial configuration is insufficient, WT and PV are abandoned as a result. The utilization ratio of distributed generation (DG) is reduced. It is converted into a cost function. The expression of converted economic cost is,

$$f_{1-2} = \sum_{t=1}^T [1 - \nu_s] Z_t \frac{r(1+r)^l}{(1+r)^l - 1} \quad (15)$$

where Z_t is the time-sharing price, r is the bank's interest rate, l is the service life of DG, ν_s is the utilization rate of renewable energy.

The lack of ESS configuration causes the electricity purchasing cost from the power grid. It is converted into a cost function, and the specific expression is,

$$f_{1-3} = \sum_{t=1}^T \sum_{s=1}^S Z_t \times \left[P_{\text{load}_s}(t) - \sum_{a_s=1}^A P_{\text{WT}_{a_s}}(t) - \sum_{b_s=1}^B P_{\text{PV}_{b_s}}(t) + \sum_{c_s=1}^C P_{\text{OV}_{c_s}}(t) \right] \quad (16)$$

where $P_{\text{load}_s}(t)$ is the load demand value/kW, A, B, C are the total number of WT, PV and other DG, S is the number of a MG in the MGs system, $P_{\text{WT}_{a_s}}$, $P_{\text{PV}_{b_s}}$, $P_{\text{OV}_{c_s}}$ are the power output of WT, PV and other DG/kW.

2) Capacity Allocation Considering Supply Demand Balance and ESS Balance Control

In the case of peak power consumption or inaccurate generation forecast, the ESS configuration capacity in the MGs cannot completely meet the demand of the load power supply. Considering the balance control of the ESS, the loss of load is converted into the cost function. The specific expression is,

$$f_{2-1} = \sum_{t=1}^T \sum_{s=1}^S \varsigma_{s,\text{loss}} \Delta P_{\text{MG}_s}(t) \\ = -\varsigma_{s,\text{loss}} \sum_{t=1}^T \sum_{s=1}^S \sum_{m=1}^M \left(\sum_{a_s=1}^A P_{\text{WT}_{a_s}}(t) + \sum_{b_s=1}^B P_{\text{PV}_{b_s}}(t) + \sum_{c_s=1}^C P_{\text{OV}_{c_s}}(t) + P_{b_m}(t) - P_{\text{load}_s}(t) \right) \quad (17)$$

where $\varsigma_{s,\text{loss}}$ is the cost coefficient corresponding to load loss, $\Delta P_{\text{MG}_s}(t)$ is the s -th MG load shortage/kW.

In a normal operational scenario, the SOC charge and discharge margin of each cell is obtained as $[\text{up_SOC}_{b_m}(t)$,

$\text{down_SOC}_{b_m}(t)]$. $P_{b_m}(t)$ is obtained, and $\sum_{t=1}^T \sum_{m=1}^M P_{b_m}$ is acquired to calculate the power output of ESS in the whole MG system. In an extreme operational scenario, the SOC charge and discharge margin of each cell is obtained as $[\max_SOC_{b_m}(t), \min_SOC_{b_m}(t)]$. $P'_{b_m}(t)$ is obtained, and $\sum_{t=1}^T \sum_{m=1}^M P'_{b_m}$ is acquired to calculate the power output of ESS in the whole MG system.

The power loss cost under the condition of unbalanced supply and demand is obtained, and the power loss cost under the extreme scenario is,

$$f_{2-2} = \sum_{s=1}^S \beta_{\text{ES}_k} \left[\left(\sum_{t=1}^T \sum_{m=1}^M P'_{b_m}(t) \sum_{t=1}^T \sum_{m=1}^M P_{b_m}(t) - \Delta P_{\text{load}_s}(t) \right) \right] \quad (18)$$

where β_{ES_k} is the cost coefficient of the ESS capacity loss, ΔP_{load_s} is the load value not absorbed by the MGs/kW.

The loss costs of the feeders around the ESS are calculated,

$$f_3 = \sum_{m=1}^M \sum_{k=1}^K \sum_{t=1}^T v_k R_k \frac{P_{b_{mk}}^2(t) + Q_{b_{mk}}^2(t)}{U_{b_{mk}}^2} dt \quad (19)$$

where v_u is the loss cost coefficient of the feeder, k is the total number of feeders, and R_k is the resistance of feeder kΩ, $Q_{b_{mk}}^2$ is reactive power.

In the capacity allocation of the ESS for echelon utilization, the optimization objectives are the whole life cycle cost of the ESS, the power loss cost of supply and demand balance and the ESS balance control. It is noted that different configuration objects value different optimization objectives. In this paper, different weights are set for multi-objective optimization, the objective function is,

$$f = \min [\xi_1 (\omega_1 f_{1-1} + \omega_2 f_{1-2} + \omega_3 f_{1-3}) + \xi_2 (\vartheta_1 f_{2-1} + \vartheta_2 f_{2-2}) + \xi_3 f_3] \quad (20)$$

where ω_1 , ω_2 , ω_3 , ϑ_1 , ϑ_2 , ξ_1 , ξ_2 and ξ_3 are the weight coefficients, and $\omega_1 + \omega_2 + \omega_3 = 1$, $\vartheta_1 + \vartheta_2 = 1$ and $\xi_1 + \xi_2 + \xi_3 = 1$ are satisfied.

In the optimization process, it is necessary to consider the priority among the objectives of life cycle cost and the priority of power loss cost corresponding to supply and demand balance in different scenarios. According to the values of the demand parameter ω_1 , ω_2 , ω_3 , ϑ_1 , ϑ_2 , ξ_1 , ξ_2 and ξ_3 , the location and capacity are established.

The reasonable capacity configuration of the ESS in MGs primarily considers the following constraints,

$$\begin{cases} P_{b_m}^{\min}(t) \leq P_{b_m}(t) \leq P_{b_m}^{\max}(t) \\ \sum_{t=1}^{24} P_{b_m}(t) \leq C_{b_m}^{\max} \\ \text{down_SOC}_{b_m} \leq \text{SOC}_{b_m}(t) \leq \text{up_SOC}_{b_m} \\ \min_SOC_{b_m} \leq \text{SOC}'_{b_m}(t) \leq \max_SOC_{b_m} \end{cases} \quad (21)$$

where $P_{b_m}^{\min}$ and $P_{b_m}^{\max}$ are the output limits of the m -th ESS in time t /kW, $\text{SOC}'_{b_m}(t)$ is the SOC characteristic of the ESS in extreme scenarios, its setting value is the upper limit value

of the ESS dynamic safety margin, $C_{b-m}^{\max}$ is the extreme value of battery capacity.

The improved fruit fly optimization algorithm (FOA) is adopted [35], the multi-objective optimization solution is carried out. The specific process is shown in Fig. 6.

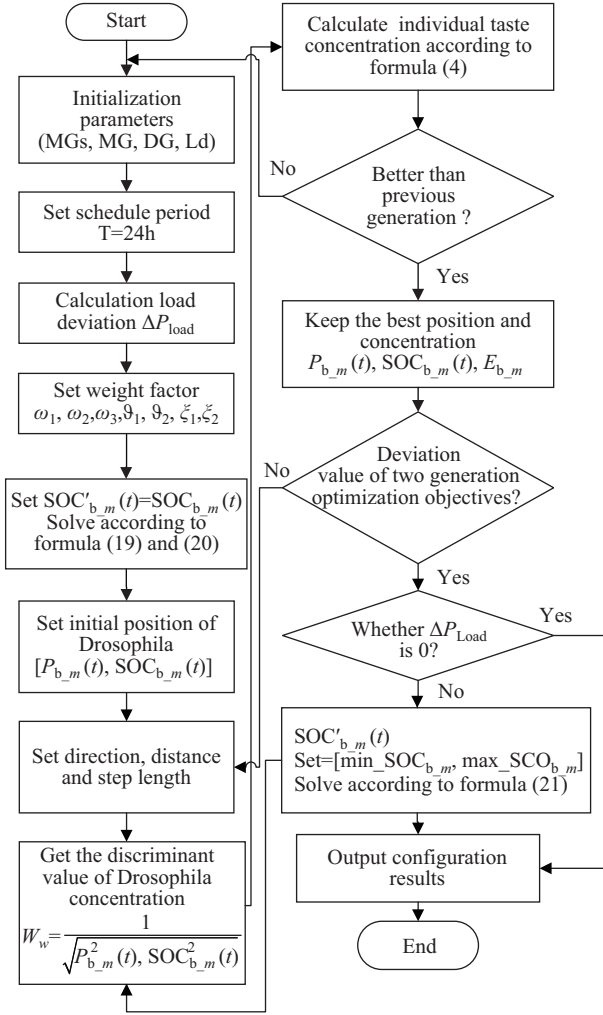


Fig. 6. Flow chart of ESS site selection and capacity determination based on FOA.

IV. SIMULATION ANALYSIS

Taking the IEEE-RTS 24 node system as an example, nodes 7, 15 and 18 are incorporated into the MG, and the architecture is shown in Fig. 7. It is estimated that the number of the ESS configured is $m = 4$, bus 13 is set as the grid connected node. The basic parameters are established as shown in Tables I to III.

TABLE I
BASIC PARAMETERS OF EACH MG

Unit	BUS 7	BUS 15	BUS 18
WT/kW	400	400	300
PV/kW	500	800	500
Micro gas turbine (MGT)/kW	50	50	50

In the accelerated life test of the ESS, the pack, composed of lithiumion batteries, is taken as an example, the rated capacity

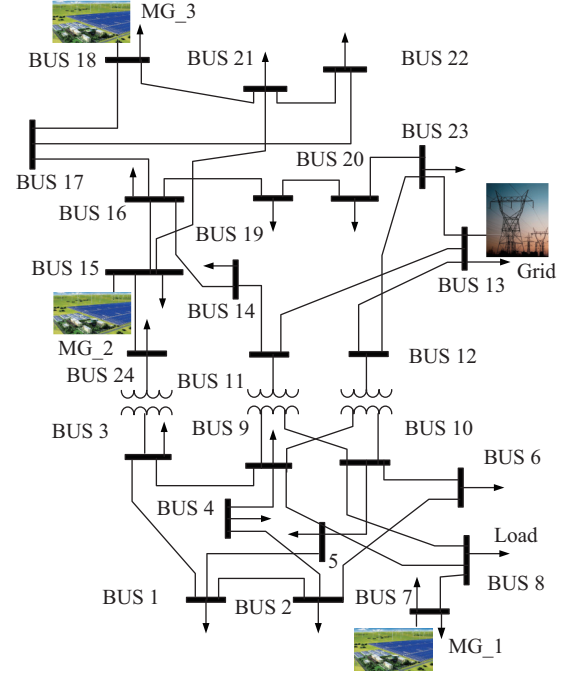


Fig. 7. Architecture form of the MG incorporated into the IEEE-RTS 24 node.

TABLE II
BASIC PARAMETERS OF INITIAL BATTERIES AND ECHELON UTILIZATION OF ELECTRIC VEHICLE BATTERIES

Initial battery	Values	Echelon utilization of electric vehicle battery	Values
Battery's capacity/Ah	50	Charge and discharge times/times	≥ 5000
Nominal voltage/V	3.2	Investment cost/(\$/Ah)	0.25
Depth of charge and discharge/%	[10, 90]	Depth of charge and discharge/%	[20, 80]
Operating voltage range/V	2.5 ~ 3.8	Unit cost saving ratio/%	30
Standard discharge current/A	100	Cost saving ratio of testing and restructuring/%	10
Expected working times/times	≥ 8000	Charging capacity ratio/%	75
Initial investment cost/(\$/Ah)	0.36	Echelon utilization ratio/%	95

TABLE III
BASIC PARAMETERS AND UNIT CAPACITY COSTS

Basic parameters	Values	Basic parameters	Values
$l_{\alpha b-m}$	$0.5 \times P_{b-m}(t)$	θ_{Dm} (\$/kWh)	0.53
α_{i0}	0.6	Z_t (\$/kWh)	0.51/0.72/1.05
α_{ix}	0.7	ζ_{s_loss}	0.3
μ_{min}	0.05	θ_{Dm} (\$/kWh)	0.53
$\min_SOC_{b-m}/\%$	0.8	K	23
$\max_SOC_{b-m}/\%$	0.2	v_u	01

is 1100 mAh. The ambient temperature is 24°C, and the initial internal resistance is 60 mΩ.

The time required for different discharge times to reach the corresponding discharge cut-off voltage is compared, as shown in Fig. 8. As the cycle number increases, the time required for the battery to reach the cut-off voltage for charge and discharge decreases. At the same time, the capacity of the battery charge and discharge is also continuously decreasing.

The reliability of the ESS is evaluated by using the anti-

power law coefficient equation, and the charge and discharge rates of 0.25C, 0.5C, 1C, and 3C are compared by using the accelerated life test, as shown in Fig. 9. It can be seen that as the charge and discharge rates increase, the SOH of the battery rapidly decreases. At the same time, the charge and discharge cycle numbers obviously decrease in the whole life cycle.

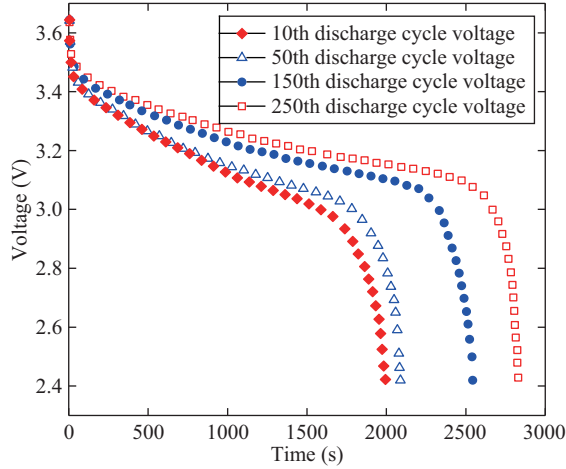


Fig. 8. Time comparison of different cycle times to reach the cut-off voltage.

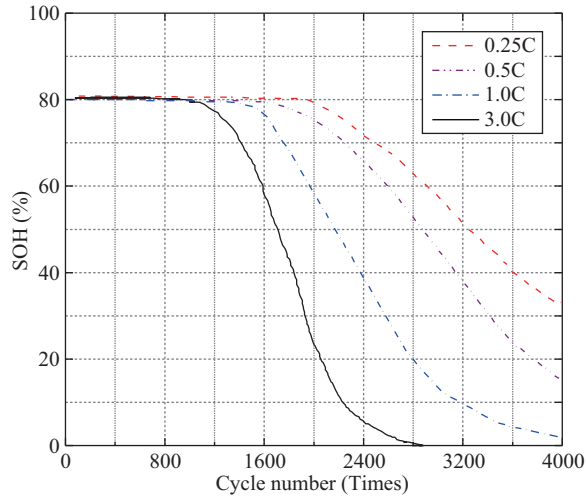


Fig. 9. SOH characteristics of batteries with different charge and discharge rates.

The influence of different charge and discharge depths on battery health is considered, as shown in Fig. 10. It can be seen that the smaller the depths of charge and discharge are, the better are the SOH characteristics. Under the same SOH, the larger the depth of discharge (DOD) is, the smaller the number of charge and discharge is.

According to the accelerated life based on the anti-power law coefficient equation, the remaining life of the ESS can be estimated, and the SOH errors corresponding to 0.5C, 1C, and 3C are respectively compared, as shown in Fig. 11. It can be seen that the average errors after 1,000 times charges and discharges are 3.09%, 2.48% and 2.84%. The adoption of accelerated life test has little impact on the estimation of SOH.

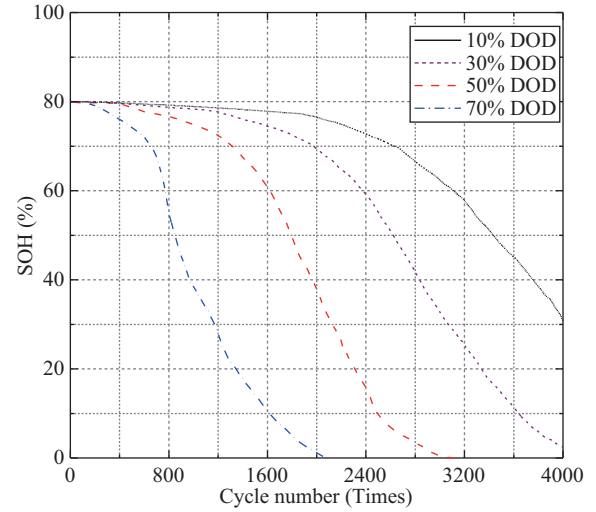


Fig. 10. The influence of different charge and discharge to SOH.

According to the test, the SOC and SOH characteristics of batteries are not the same under different charge and discharge depths. Batteries are used in echelon utilization, it is composed of the same battery group with similar SOH characteristics, but there are differences in the SOH among battery packs. In order to solve this problem, when the MG optimizes the configuration of the ESS, the capacity allocation method is proposed based on the SOC dynamic security margin, the basic architecture and parameters of the MG's access to the IEEE-RTS 24 node. The typical daily load curve of each MG and grid node is shown in Fig. 12.

First, when the ESS capacity of echelon utilization is configured, the life decay degree is determined according to different charge and discharge depths. Considering SOH, time-sharing price and the average value of annual power deviation in the system, the dynamic safety margin of the ESS is determined, as shown in Fig. 13.

It can be seen that $SOC_{b,m}$ is set between [20%, 80%]. From 9:00 to 21:00, $SOC_{b,m}$ is set between [25%, 75%]. A safety margin is reserved for each period to improve the reliability of the power supply in extreme cases.

Secondly, the initial SOC and SOH of each unit in the echelon utilization ESS are different, and the equalization control of each ESS is considered. 3 groups of typical battery modules (B1, B2, B3) in ESS 1 are selected to compare the SOC characteristics, which are shown in Fig. 14.

According to Fig. 14, when the equalization control is not used, each battery reaches the same SOC value after charging. When using the equalization control, each cell has an optimal SOC value according to the difference of the initial characteristics of each cell. The life loss caused by the increase of charging depth is effectively avoided.

In order to further determine the benefits of equilibrium control, the average health of the whole ESS under different charge and discharge numbers is shown in Fig. 15.

According to the selection of different weight coefficients to determine the focus of optimization objectives, the capacity configuration of the ESS is shown in Table IV.

It can be seen from Table IV that the weight coefficient is set

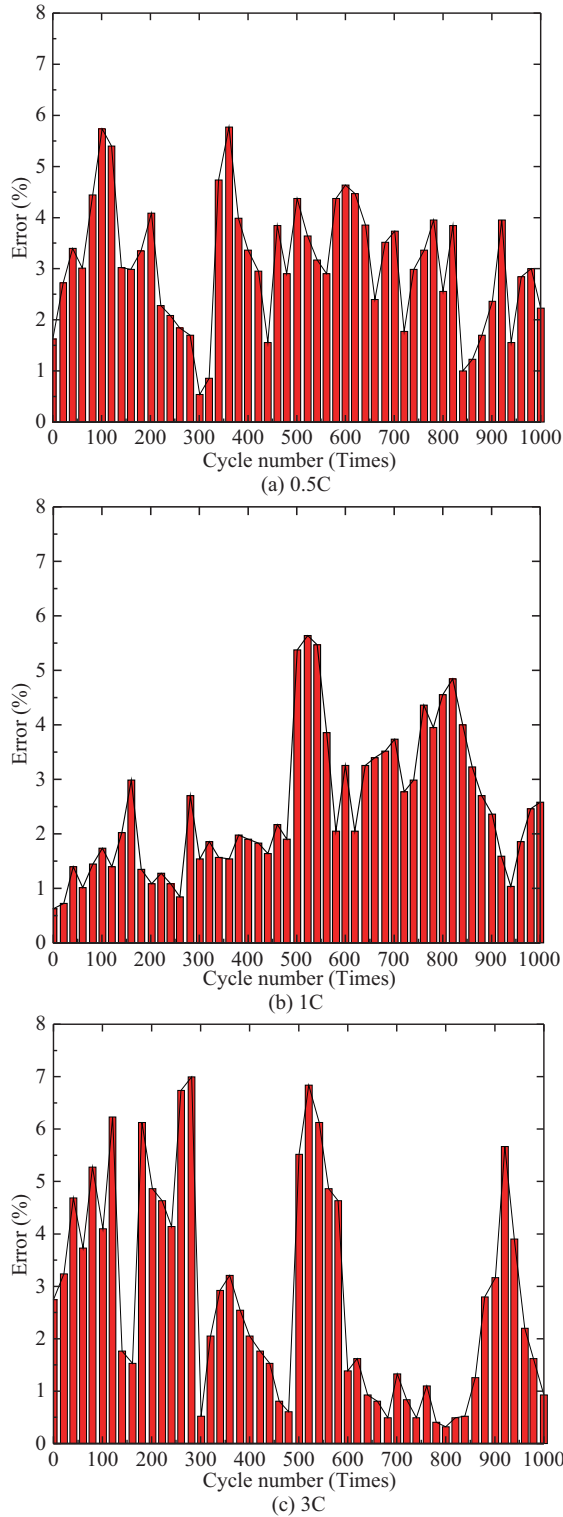


Fig. 11. Comparison of the error life under different times.

for multi-objective optimization solutions, and the differences of the weight results in certain differences in location and capacity of the ESS. When the weight coefficients are set to $\omega_1 = 1/3$, $\omega_2 = 1/3$, $\omega_3 = 1/3$, $\vartheta_1 = 1/2$, $\vartheta_2 = 1/2$, $\xi_1 = 1/3$, $\xi_2 = 1/3$, $\xi_3 = 1/3$, the limit value of the $\Delta SOC_{b,m}$ is determined according to SOH, and the specific grid connection node and capacity are determined. When the

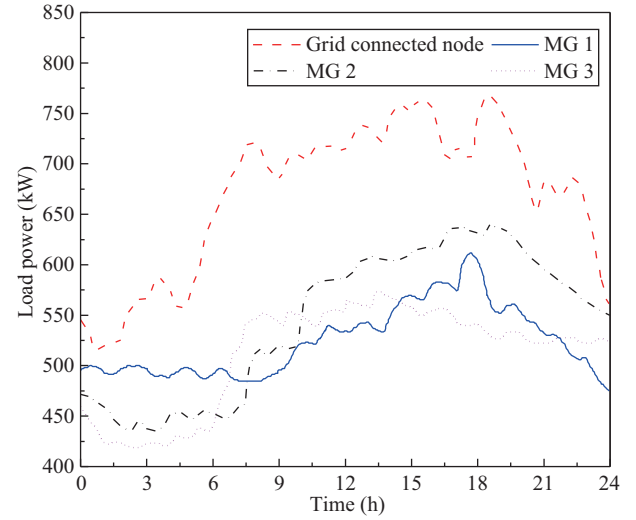


Fig. 12. Typical daily load curve.

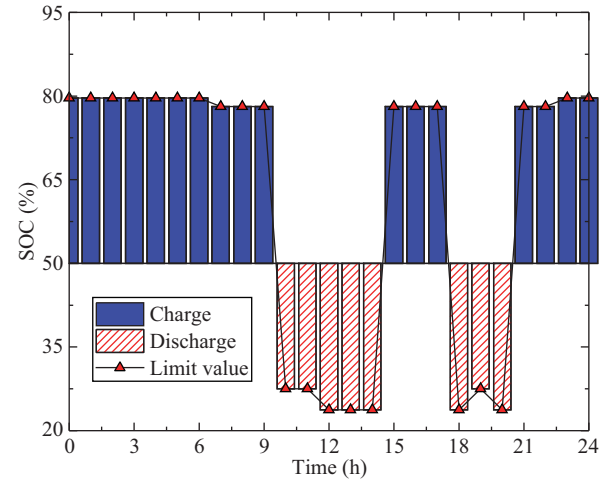


Fig. 13. Set the safety margin of the SOC.

TABLE IV
SITE SELECTION AND CAPACITY ALLOCATION OF THE ESS

First configuration	ESS 1	ESS 2	ESS 3	ESS 4
Set weight	$\omega_1 = 1/3, \omega_2 = 1/3, \omega_3 = 1/3, \vartheta_1 = 1/2, \vartheta_2 = 1/2, \xi_1 = 1/3, \xi_2 = 1/3, \xi_3 = 1/3$			
Interconnection node	2	16	17	19
Grid-connected capacity/kWh	113	148	100	30
Extreme Value of $\Delta SOC/\%$	60	53	51	55
Second configuration	ESS 1	ESS 2	ESS 3	ESS 4
Set weight	$\omega_1 = 1/4, \omega_2 = 1/4, \omega_3 = 1/2, \vartheta_1 = 1/5, \vartheta_2 = 4/5, \xi_1 = 1/4, \xi_2 = 1/4, \xi_3 = 1/2$			
Interconnection node	8	24	21	23
Grid-connected capacity/kWh	142	188	128	50
Extreme Value of $\Delta SOC/\%$	50	52	48	46
Third configuration	ESS 1	ESS 2	ESS 3	ESS 4
Set weight	$\omega_1 = 1/5, \omega_2 = 2/5, \omega_3 = 2/5, \vartheta_1 = 1/2, \vartheta_2 = 1/2, \xi_1 = 1/2, \xi_2 = 1/4, \xi_3 = 1/4$			
Interconnection node	2	24	21	23
Grid-connected capacity/kWh	192	215	162	65
Extreme Value of $\Delta SOC/\%$	56	58	57	53

weight coefficients are set to $\omega_1 = 1/4$, $\omega_2 = 1/4$, $\omega_3 = 1/2$, $\vartheta_1 = 1/5$, $\vartheta_2 = 4/5$, $\xi_1 = 1/4$, $\xi_2 = 1/4$, $\xi_3 = 1/2$, the weight coefficient corresponding to the feeder loss cost is the largest. The locations of ESS 1, 2, 3 are at node 8, 24, 21, the

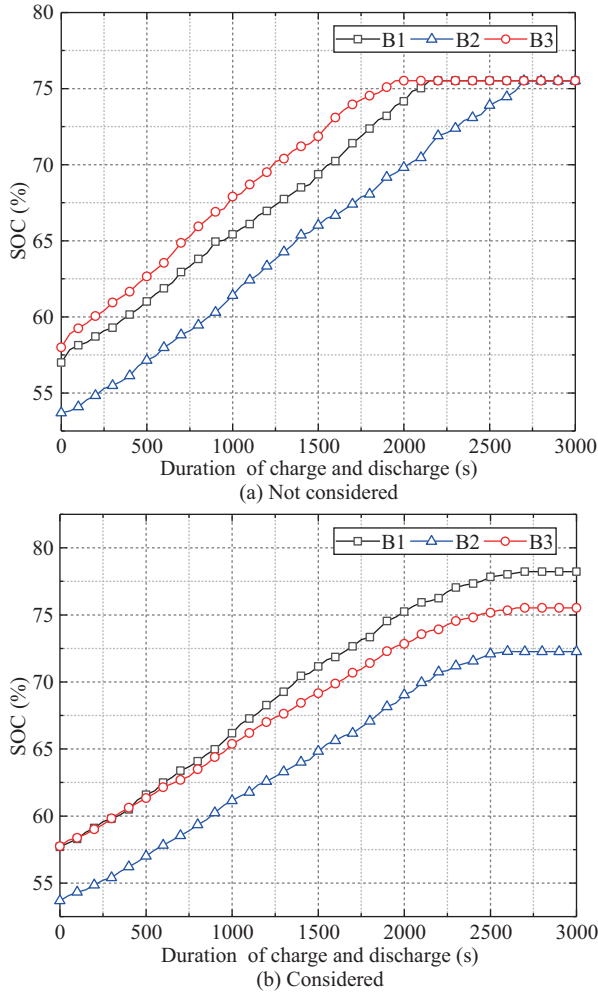


Fig. 14. SOC comparison chart of equalization control when charging.

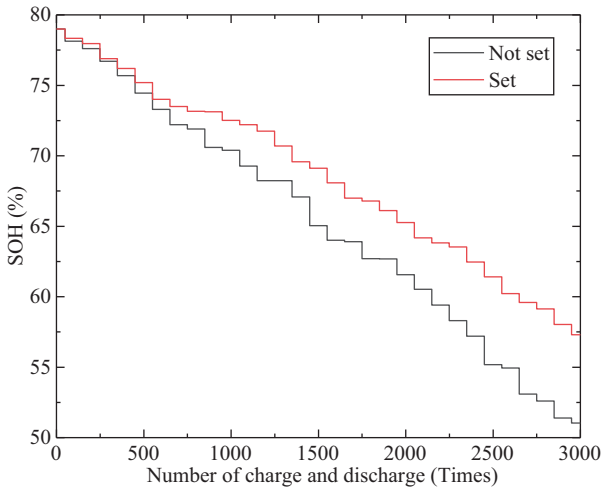


Fig. 15. SOH comparison of ESS with dynamic safety margin setting.

location of the centralized ESS is at node 23, and the location of ESS is near the MG to reduce the feeder loss cost. Under the condition of unbalanced supply and demand in extreme scenarios, the corresponding weight setting of the power loss cost is too large, the limit value of ΔSOC_{b-m} is too large, and

the reserved safety margin is too large to meet the balance of supply and demand. When the weight coefficients are set to $\omega_1 = 1/3$, $\omega_2 = 1/3$, $\omega_3 = 1/3$, $\vartheta_1 = 1/5$, $\vartheta_2 = 4/5$, $\xi_1 = 1/4$, $\xi_2 = 1/4$, $\xi_3 = 1/2$, the weight setting of the energy loss cost and power purchase cost of ESS is too large, and the capacity setting of each ESS is larger than the first two cases.

When the weight coefficients are set to $\omega_1 = 1/3$, $\omega_2 = 1/3$, $\omega_3 = 1/3$, $\vartheta_1 = 1/5$, $\vartheta_2 = 4/5$, $\xi_1 = 1/4$, $\xi_2 = 1/4$, $\xi_3 = 1/2$, the payback period is 10 years, the differences of costs corresponding to the target function are compared and analyzed to see whether the echelon utilization is in the fifth year, as shown in Fig. 16.

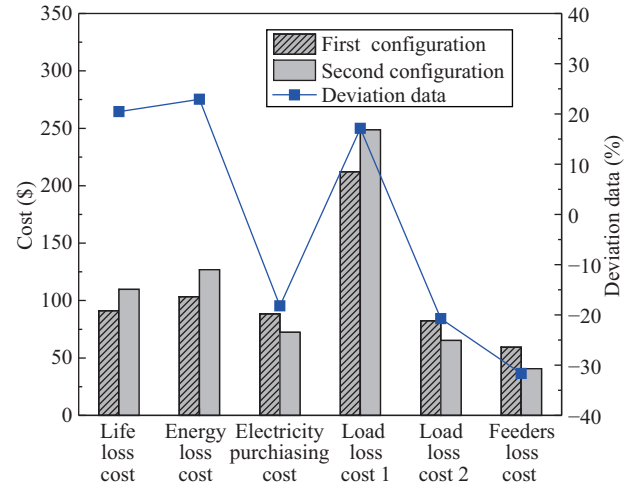


Fig. 16. Cost comparison of echelon ESS.

The first and second configuration scenarios are considered, and the difference of cost corresponding to the target function of the electric vehicle power battery is adopted. It can be seen that in scenario 2, the above three weights are set to $\omega_3 = 1/2$, $\vartheta_2 = 4/5$, $\xi_3 = 1/2$. Compared with the first scenario, the optimization target cost is relatively reduced, taking the feeder loss cost as an example, the cost is reduced by 31.7%, the cost of load loss in a typical scenario increased by 17.1%.

The influence of setting ΔSOC as the ESS configuration is considered, the weight coefficients are set to $\omega_1 = 1/3$, $\omega_2 = 1/3$, $\omega_3 = 1/3$, $\vartheta_1 = 1/2$, $\vartheta_2 = 1/2$, $\xi_1 = 1/3$, $\xi_2 = 1/3$, $\xi_3 = 1/3$, the influence of ΔSOC_{b-m} is different when this configuration is not considered, the specific configuration is shown in Table V.

TABLE V
SITE SELECTION AND CAPACITY ALLOCATION OF ESS WHEN ΔSOC_{b-m} IS NOT CONSIDERED

Name	ESS 1	ESS 2	ESS 3	ESS 4
Set weight	$\omega_1 = 1/3$, $\omega_2 = 1/3$, $\omega_3 = 1/3$, $\vartheta_1 = 1/2$, $\vartheta_2 = 1/2$, $\xi_1 = 1/3$, $\xi_2 = 1/3$, $\xi_3 = 1/3$			
Interconnection node	2	16	17	19
Grid-connected capacity/kWh	106	138	91	29
Extreme Value of $\Delta SOC/\%$	60	60	60	60

According to Table V, when the difference of ΔSOC_{b-m} is not considered, $\Delta SOC_{b-m} = 60\%$ is set, the configuration of ESS 1, 2, 3, 4 are reduced from the original 113 kWh, 148

kWh, 100 kWh, 30 kWh to 106 kWh, 138 kWh, 91 kWh, 29 kWh, in which the ESS 1 capacity without changing ΔSOC_{b_m} is also reduced by 6.80%, and the power interaction between the MGs is explained. The capacity of ESS 2, 3, 4 decreased by 6.75%, 9.00%, 3.33%.

ΔSOC_{b_m} is set, the impact of the SOH characteristics and the optimization target cost are compared, as shown in Fig. 17.

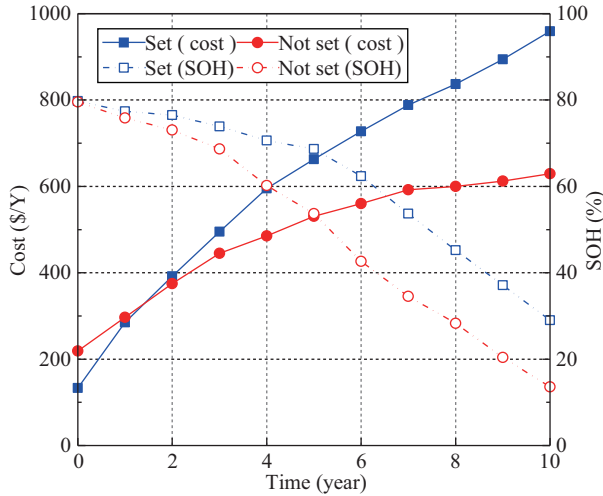


Fig. 17. Trend chart of SOH and ESS target cost.

The setting SOC influence on the power output and SOC of the grid connected nodes is shown in Figs. 18 and 19.

It can be seen in Fig. 17 that if ΔSOC_{b_m} is not set, the target cost of capacity configuration is reduced, but the SOH characteristics are significantly reduced. If ΔSOC_{b_m} is set, the initial target cost of echelon ESS is reduced, the target cost of capacity configuration is slightly increased, but the SOH characteristics are significantly improved.

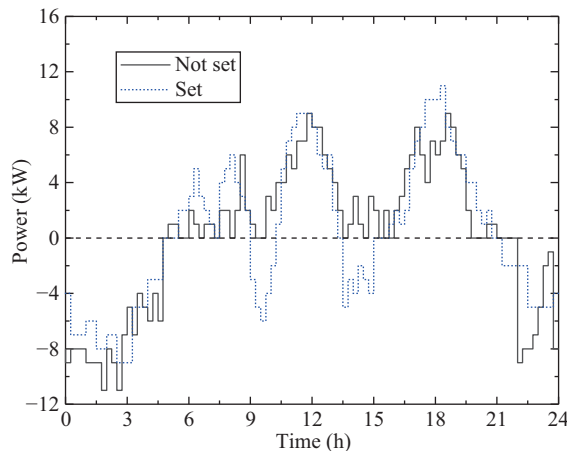


Fig. 18. Comparing the ESS4 power output of the setting SOC.

It can be seen in Fig. 18 that without considering SOC, the valley time charging can meet the power demand in normal and peak times. Considering SOC, it needs to purchase power from the grid in normal times, but it can better respond to the demand in peak hours. The charging is smoother in the valley time, which indirectly improves the life of the ESS.

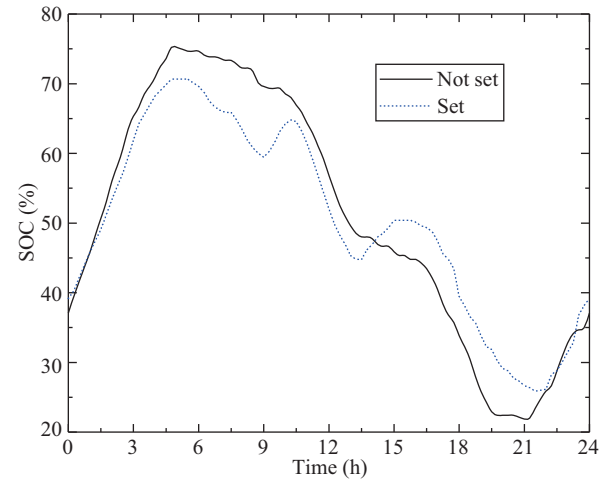


Fig. 19. Comparing SOC changes of the ESS4.

It can be seen in Fig. 19 that the SOC is within the setting range of the dynamic safety margin. The SOC safety margin is established to effectively reduce the depth of charge and discharge, and the operational life is indirectly increased.

V. CONCLUSION

In order to promote the echelon utilization of the power battery in decommissioning, taking the MG as the object, the location and capacity configuration of the ESS are carried out. The conclusions are as follows.

First, an accelerated life test method based on the anti-power law coefficient equation is proposed. It is used to evaluate the reliability of the ESS. Compared with the test data, the reliability evaluation method has a high accuracy for residual life prediction. The error of the 3C accelerated life test is only 0.36% more than 1C. The time required for life assessment is reduced. It lays a foundation for the rationality and accuracy of the recombining and configuration of the single battery.

Secondly, an ESS capacity allocation method based on the dynamic security margin is proposed, which fully considers the cost of the ESS life loss, SOH, typical daily scenario and extreme daily scenario power loss cost, etc. When the SOC dynamic security margin is set in the configuration, the requirements of the maximum capacity configuration are increased by 9%. The maximum cost reduction is 31.7% and the SOH is increased by 32.0% in the 10th year.

Finally, when the ESS dynamic safety margin is considered, the centralized grid connected power output and SOC characteristics are compared. The reasonable optimization configuration effectively extends the service life of the ESS, and improves the accuracy of the capacity configuration of the ESS.

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