Optimal Whole-Life-Cycle Planning for Battery Energy Storage System with Normalized Quantification of Multi-Services Profitability

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Abstract

The application services of the battery energy storage system (BESS) in the power system are more diverse, such as frequency regulation, peak shaving, time-shift arbitrage, etc. However, it is challenging to achieve the maximum revenue for one BESS providing multi-services in the whole life cycle due to the different life degradation and economic performance among variable services. This paper proposes optimal whole-life-cycle planning with normalized quantification of multi-services profitability. The proposed planning is designed to discretize battery lifespan into multi-cycle-life scales and apply the most profitable service in each scale by evaluating the proposed cycle-life opportunity benefit of all the available services, which is used to uniformly quantify their profitability, and dynamically setting the cycle-life scale based on the variation of cycle-life opportunity benefits. An improved model is obtained for the battery life degradation by considering the impacts of the actual discharge current on the actual capacity in each discharge process. The planning in the application services of frequency regulation and time-shift arbitrage is tested under practical market rules and actual operation strategies. The result with the comparison to the individual, stacked, and successive services schemes validate that the overall benefits of the proposed planning are increased by 39.9%, 34.8%, 138.5%, and 13.2%, respectively, and even higher revenue can be achieved when the proposed planning accounts for more than two services.

Keywords

battery energy storage system; whole life cycle; multi-services planning; battery life degradation model

Abbreviation

BESS	Battery Energy Storage System
DOD	Depth of Discharge
SOC	State of Charge
SOH	State of Health
NPV	Net Present Value

Nomenclature

Cycle-life degradation model parameters

D_R	Percent DOD at which rated life was determined
D_A	Actual discharge as a percentage of rated capacity
N_R	Number of life cycles at rated DOD and rated discharge current

N_{A}	Number of life cycles at a given percent discharge and discharge current
Γ_{R}	Amp-hour life of a cell under repeated discharges of rated DOD and rated discharge current
C_{R}	Amp-hour capacity of a cell at a rated discharge current
C_{A}	Amp-hour capacity of a cell at a given discharge current
d_{actual}	Actual amp-hour discharge
d_{eff}	Effective amp-hour discharge as adjusted for depth and rate of discharge
I_{A}	Discharge current(A)

Different application services benefit calculation parameters

f_0, $f(t)$	System-rated frequency and real-time frequency at time t (Hz)
Δf_{R}, Δf_{DB}	System rated frequency deviation and dead band frequency (Hz)
$K_{\mathrm{BAT}}(t)$	P-f characteristic coefficient of battery at time t
$P_{\mathrm{BAT.max}}$	Battery-rated power (MW)
$C_{\mathrm{BAT.max}}$	Battery-rated capacity (MWh)
K_f	Comprehensive performance index of frequency regulation
T_{MON}	Monthly frequency regulation ancillary service market trading cycles
D^i	i-th planning period frequency regulation mileage of BESS (MW)
Q^i	i-th planning period mileage settlement price (CNY/MW)
r	Discount rate
C^i	i-th planning period AGC capacity of BESS (MW)
T^i	i-th planning period frequency regulation service duration of BESS (h)
s^i	i-th planning period AGC capacity compensation (CNY/MWh)
ΔP^i	i-th planning period BESS frequency regulation difference (MW)
ρ^i_{PEN}	i-th planning period electricity penalty price (CNY/MWh)
E^i_{BUY}	i-th planning period purchased electricity of BESS (MWh)
ρ^i_{BUY}	i-th planning period electricity price (CNY/MWh)
$P^i_{\mathrm{DIS}}/P^i_{\mathrm{CHA}}$	i-th planning period discharge/charge power of BESS (MW)
$\rho^i_{\mathrm{PEAK/VALL}}$	Peak and valley electricity price (CNY/MWh)
ρ_{MAIN}	Operation& maintenance cost of BESS per unit power (CNY/MW/day)
ρ_{REP}	Capacity replacement cost of BESS per unit capacity (CNY/MWh)
ρ_{P}	The construction cost of BESS per unit power (CNY/MW)
ρ_{C}	The construction cost of BESS per unit capacity (CNY/MWh)
m, m_{CAL}	The year BESS has been in operation and the calendar life limit (year)
E^i_{REG}	i-th planning period peak shaving electricity of BESS (MWh)
ρ^i_{REG}	i-th planning period peak shaving price (CNY/MWh)

BESS operating parameters

$C_{\mathrm{BAT}}(t)$	Battery energy capacity at time t (MWh)
$SOC_{\mathrm{BAT}}(t)$	Battery state of charge (SOC) at time t
δ	Battery self-discharge rate
$\theta_{\mathrm{CHA}}/\theta_{\mathrm{DIS}}$	Battery round-trip efficiency
$SOC_{\mathrm{BAT.min/max}}$	Battery SOC upper and lower limits

1. Introduction

To meet sustainable development goals (SDGs) by the year 2030 (Aly et al., 2022), a battery energy storage system (BESS) has been systematically investigated as a proven solution to effectively balance energy production and consumption (Hannan et al, 2020), and further realize the cleaner and low-carbon grids of the future (Martins and Miles, 2021). Moreover, with the constant improvement of the electricity market operation regulation, BESS has been fully involved in a number of services in the electricity market, and even deeply participates in electricity market transactions as an independent identity (Gaspar et al, 2021). The cumulative installed capacity of BESS in the global electricity market was 14.2GW by the end of 2020, with a year-on-year growth of 49.6%.

There are two categories of BESS applications according to different operating characteristics: 1) Power-type application has the characteristics of high power charge/discharge and shallow depth of discharge (DOD), which accelerate the degradation of the battery life, such as primary frequency regulation (Oudalov et al, 2007), secondary frequency regulation auxiliary service (Wang et al, 2021), and suppressing the fluctuation of renewable energy resources (RERs) output (Jiang et al, 2021). 2) Energy-type application has low power charge/ discharge and deep DOD, which result in the slow degradation of battery life. The typical services include black start (Li et al, 2020), peak shaving (Sun et al, 2020), and energy time-shift arbitrage (Walawalkar et al, 2007).

Early researches are most focused on the service performance of BESS in the electricity market. (Sasaki et al, 2004) points out that the utilization of BESS can replace the conventional automatic gain control (AGC) units without compromising on frequency regulation performance. The results of (Cheng et al, 2014) show that the frequency control capacity of BESS can respond up to 10 times faster than that of fossil power systems due to quick response characteristics. The life-cycle cost of the long-duration and short-duration energy storage (Schoenung and Hassenzahl, 2003), sensitivities to various input assumptions (Schoenung and Hassenzahl, 2007), and the update cost (Schoenung, 2011) are comprehensively investigated in a series of technical reports.

(Walawalkar et al, 2007) indicates that BESS has a high probability of positive benefits net present value (NPV) for both regulation services and energy arbitrage. The economic profitability of the BESS frequency regulation service is obtained based on dimensioning (Oudalov et al, 2007) and operation optimization control strategies (Mercier et al, 2009). The profit maximization problem of the BESS-based energy arbitrage is discussed under different operation conditions: (Cui et al, 2018) proposes a bilevel battery arbitrage strategy in deregulated power systems with high-penetration wind power; (Cao et al, 2020) offers a deep reinforcement learning (DRL) based method for BESS participating in the energy arbitrary considering the accurate battery degradation model; (Krishnamurthy et al, 2018) provides a stochastic formulation of one BESS owner's arbitrage profit under the conditions of day-ahead and real-time market price uncertainty. Most of the above studies only concentrate on one specific service from the BESS in the electricity market; however, recent research turns to one BESS stacked utilization for multi-services to maximize the benefits in the whole life cycle (Pudjianto et al, 2014).

The concept of the stacked application, i.e. participating in multi-application simultaneously, is previously introduced in vehicle-to-grid (V2G), (White and Zhang, 2011) proposes the profit scheme for both frequency regulation and peak reduction using V2G technology, the profits are higher than either of the two individual services on their own. The stacked application can also be applied to provide the optimization framework of BESS for multi-services simultaneously with variable and stochastic energy and power requirements, such as: energy arbitrage and fast frequency response (Pusceddu et al, 2021), peak shaving and frequency regulation (Shi et al, 2018), and demand peak shaving and price arbitrage business (Schneider et al, 2021). The battery degradation model presented in the above works is in simplified linear form, which can only apply to a certain battery operation range. The battery degradation model through the dynamic procedure is proposed to arrange BESS for participation in frequency regulation and energy markets simultaneously (Kazemi and Zareipour, 2018).

However, stacked utilization has drawbacks such as increased battery replacement cost (Świerczyński et al, 2014) and accelerated depreciation of the battery (Yang et al, 2021) due to frequent and deep charge/discharge cycles. In addition, although battery recycling technology has made great progress compared with twenty years ago (Bernardes et al, 2004), it has not been properly and reasonably developed (Jin et al, 2022), which emissions toxic metals and corrosive chemicals to the environment (Kim et al, 2021). Therefore, for the purpose of balancing general revenue and battery service lifespan, the optimal BESS planning schemes for providing the multi-services are presented in the current research. (Kazemi and Zareipour, 2018) defines the optimal capacity of the battery by two limiting factors in the different services, so that the BESS in each service can deliver its commitments and optimize its profits for a long time.

(Zhang et al, 2020) contributes to proposing a novel BESS whole-life-cycle plan. Battery life degradation is modeled based on the relationship between the number of cycles and DOD, without considering the impact of the discharge current on the actual capacity. Moreover, the battery life degradation is regarded as a constraint of the benefit objective function in the proposed planning which realizes the balance between extending BESS's lifespan and maximizing its revenue. Furthermore, the optimal planning is calculated using the differential evolutionary algorithm to schedule the frequency regulation service and load-shifting service. But the calculation process will be complex if the multiple decision variables increase when the planning covers more than two services.

In this paper, optimal whole-life-cycle planning for BESS with normalized quantification of multi-services profitability is proposed. This paper aims to maximize the profitability of BESS under a variety of services, with full consideration of the BESS operation efficiency and reliability. The relationship between the battery life degradation and BESS service benefit is described by introducing one economic definition of the opportunity benefit as a new index. Opportunity benefit is the benefit of making one choice while giving up all other choices under the premise of consuming the same "resources", which is used to measure the economic performance of different decision-making plannings (Branca et al, 2021). Consequently, the cycle-life opportunity benefit is introduced as the benefit of selecting one service while giving up all other services under the premise of consuming the same "scale of battery cycle-life" in the BESS optimal planning. Specifically, the BESS's owner calculates the cycle-life opportunity benefits of the different available services and selects the highest one as the application in the first life segment. And then, the cycle-life opportunity benefits are re-calculated in each cycle-life scale, the application will be switched to another service for the next life segment once the current service is not the highest cycle-life opportunity benefit one. The length of the cycle-life scale will be adjusted dynamically if the differences in the cycle-life opportunity benefits between the current service and the other services have been changed. Furthermore, the case studies of the conventional methods and proposed method are implemented, using existing market rules and actual operation data, to verify the effectiveness of the proposed planning. The main contributions and innovations are as follows:

1) An improved model is obtained for the battery life degradation by considering the impacts of the actual discharge current on the actual capacity in each discharge process.
2) The proposed planning optimizes the decision-making process of selecting the most profitable BESS services in the whole life-cycle by uniformly quantifying the profitability of all the available services and dynamically setting the cycle-life scale.
3) Compare to the existing individual, stacked, and successive services schemes, the proposed planning can achieve overall benefits maximization, and even higher revenue can be achieved when the proposed planning accounts for more than two services.

This paper is organized as follows: the BESS cycle-life degradation model is introduced in Section 2; and then, Section 3 describes the benefit calculation rules for different application services; moreover, the cycle-life opportunity benefit and the multi-services planning are proposed in Section 4; Section 5 compares and analysis the case studies results of the different BESS planning schemes; finally, conclusions are drawn in Section 6.

2. Battery cycle-life degradation modeling

In the study of BESS's whole life cycle planning, the battery cycle lifespan is a key quantitative factor of BESS's state of health (SOH). It is set as the nominal lifespan under rated operating conditions in a common battery degradation model. However, the lifespan of a battery is closely related to its charging/discharging strategies, operating environment (ambient temperature, environmental humidity, material aging, etc.), and other factors during the on-site operation. The deviation of the actual DOD from the rated DOD will directly affect the battery cycle lifespan. Therefore, based on the static function of BESS in the power system, this paper establishes a BESS cycle-life degradation model based on the relationship between the actual number of cycles and DOD during the battery on-site operation (Belouda et al, 2016). Fig. 1 shows the relationship between the number of cycles and the DOD of a 1MW/ 2MWh lithium iron phosphate battery, and the detailed specifications will be introduced in Section 5. Similar curves can also be applied to other different types of batteries. In the same operating environment, the number of life cycles is the decreasing function of DOD. Based on empirical data, the fitted functional relationship between the cycle number N_A and the DOD D_A can be expressed as follows:

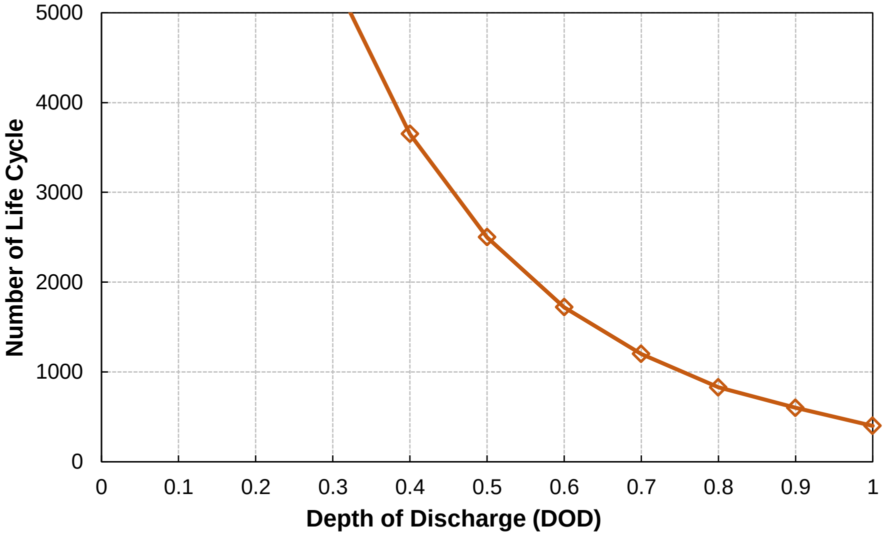

Fig. 1 The relationship between the number of cycles and the DOD of a lithium iron phosphate battery

$$N_A = N_R \times \left(\frac{D_R}{D_A}\right)^{\mu_0} \times e^{\mu_1\left(1-\frac{D_A}{D_R}\right)} \quad (1)$$

where μ_0 and μ_1 are the life cycle curve fitting parameters. The total effective electricity of BESS during its service life under the rated discharge depth is shown as:

$$\Gamma_R = N_R D_R C_R \quad (2)$$

Previous studies have shown that the effective electricity corresponding to the rated DOD is a certain value. Once the accumulated effective electricity is equal to the rated value, BESS will be forced to scrap. The actual discharge during a single discharge process d_{actual} can be converted to the effective discharge d_{eff} at the rated DOD, as shown below:

$$d_{\mathrm{eff}}=\left(\frac{D_{\mathrm{A}}}{D_{\mathrm{R}}}\right)^{\mu_0}\times e^{\mu_1\left(\frac{D_{\mathrm{A}}}{D_{\mathrm{R}}}-1\right)}\times\left(\frac{C_{\mathrm{R}}}{C_{\mathrm{A}}}\right)^{v_0}\times e^{v_1\left(\frac{C_{\mathrm{R}}}{C_{\mathrm{A}}}-1\right)}d_{\mathrm{actual}} \quad (3)$$

where v_0 and v_1 are the fitting parameters. Since D_{R} is a constant rated value, therefore the value of d_{eff}, which characterizes the cycle-life degradation, is related to variables D_{A}, C_{A}, and d_{actual}. When high capacity charging and discharging, D_{A} and d_{actual} are larger, C_{A} is smaller, so the calculated effective discharge d_{eff} is larger, the corresponding cycle-life decay is faster, and vice versa, which is consistent with reality. And when the DOD and charge-discharge rate of cycles are the same, i.e. D_{A}, C_{A}, and d_{actual} are the same, the cycle-life degradation of each cycle can be regarded as equal, in this case, the life degradation is linearly related to the number of cycles. It is assumed that the BESS operates in a stable environment, and environmental factors such as temperature are considered to remain approximately constant. In previous studies, the actual ampere-hour capacity C_{A} under different discharge currents I_{A} is considered to be a constant, which is roughly considered that $C_{\mathrm{A}}=C_{\mathrm{R}}$. However, from Fig. 2 the C_{A} corresponding to different I_{A} are quite different, which will affect the calculation accuracy of d_{eff} (Belouda et al, 2016), so the relationship between them needs to be clarified. The functional relationship between C_{A} and I_{A} obtained by n-th order polynomial fitting is as follows:

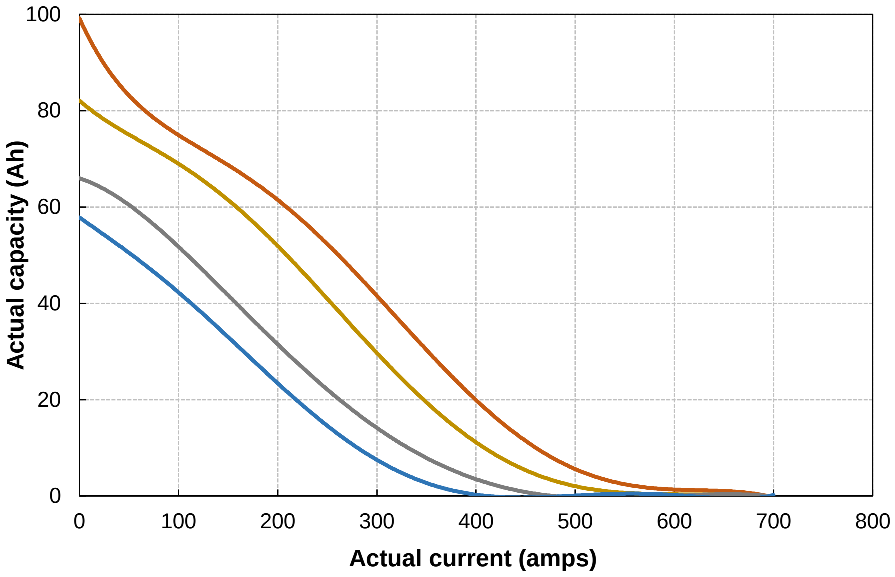

Fig. 2 The actual capacity and discharge current of several batteries (the rated capacity of the batteries in the figure are 58, 67, 82, and 98 amps respectively from bottom to top)

$$C_{\mathrm{A}}=a_nI_{\mathrm{A}}^n+a_{n-1}I_{\mathrm{A}}^{n-1}+\ldots+a_1I_{\mathrm{A}}+a_0\ ;a_n,a_{n-1},\ldots,a_1,a_0\in R \quad (4)$$

where a_0, a_1,..., a_n are the fitting coefficients. Combined with Eq. (1)-(4), the BESS cycle-life degradation percentage $\mathrm{d}\Gamma$ within the operating time T can be obtained as follows:

$$\mathrm{d}\Gamma = \frac{\Gamma_{\mathrm{eff}}}{\Gamma_{\mathrm{R}}} = \frac{\sum_{i=1}^{T}\sum_{n=1}^{N} {d_{\mathrm{eff}}}^{(i,n)}}{N_{\mathrm{R}} D_{\mathrm{R}} C_{\mathrm{R}}} \quad (5)$$

where N is the number of discharge processes in the i-th planning period, and T is the number of periods. From Eq. (5), the lifespan of the battery is varied by multi factors during on-site operation, and the cycle-life degradation is closely related to the power system demand for its charging/ discharging.

3. Different service operation rules

For the purpose of easy understanding in the proposed whole-life-cycle multi-services planning, the operation rules of BESS under different services should be introduced at the beginning. As mentioned above, services can be divided into two types: power-type application, and energy-type application. We select two corresponding typical services respectively, which are frequency regulation auxiliary service and energy time-shift arbitrage.

3.1 Frequency regulation auxiliary service

3.1.1 BESS power control strategy

The BESS input/output power is mainly determined by the grid frequency deviation and battery power-frequency (P-f) characteristic. To avoid unnecessary frequent utilization of BESS and slow down the attenuation of the equipment lifespan, it is necessary to set the dead band for input/output power. Besides, due to the power constraint, the P-f characteristic of BESS participating in frequency regulation is a piecewise function, as shown in Fig. 3.

Chinese GB/T 15945 "Power quality power system frequency permissible deviation" standard stipulates: that the standard national power grid frequency is 50 Hz, and the frequency deviation does not exceed ±0.2 Hz. GB/T 30370 "Guidelines for primary frequency control test and performance acceptance of thermal power units" standard stipulates that the dead band of the primary frequency compensation is 50 ± 0.033 Hz. Therefore, we set the frequency reference value f_0=50 Hz, dead band Δf_{DB}=0.033 Hz, and rated frequency deviation Δf_{R}=0.2 Hz. The relationship between the BESS P-f characteristic coefficient $K_{\mathrm{BAT}}(t)$ and the real-time frequency $f(t)$ is as follows:

$$K_{\mathrm{BAT}}(t)=\begin{cases} 0, & \Delta f=\left|f(t)-f_0\right|\leq \Delta f_{\mathrm{DB}} \\ P_{\mathrm{BAT.max}}/(\Delta f_{\mathrm{R}}-\Delta f_{\mathrm{DB}}), & \Delta f_{\mathrm{DB}}<\Delta f=\left|f(t)-f_0\right|\leq \Delta f_{\mathrm{R}} \\ P_{\mathrm{BAT.max}}/(\Delta f-\Delta f_{\mathrm{DB}}), & \Delta f=\left|f(t)-f_0\right|>\Delta f_{\mathrm{R}} \end{cases} \quad (6)$$

And then BESS t-period charge/discharge strategy is obtained as:

$$P_{\mathrm{BAT}}(t)=\begin{cases} P_{\mathrm{CHA}}(t)=K_{\mathrm{BAT}}(t)\left(f_0-\Delta f_{\mathrm{DB}}-f(t)\right), & f(t)\leq f_0-\Delta f_{\mathrm{DB}} \\ 0, & f_0-\Delta f_{\mathrm{DB}}<f(t)\leq f_0+\Delta f_{\mathrm{DB}} \\ P_{\mathrm{DIS}}(t)=K_{\mathrm{BAT}}(t)\left(f_0+\Delta f_{\mathrm{DB}}-f(t)\right), & f(t)>f_0+\Delta f_{\mathrm{DB}} \end{cases} \quad (7)$$

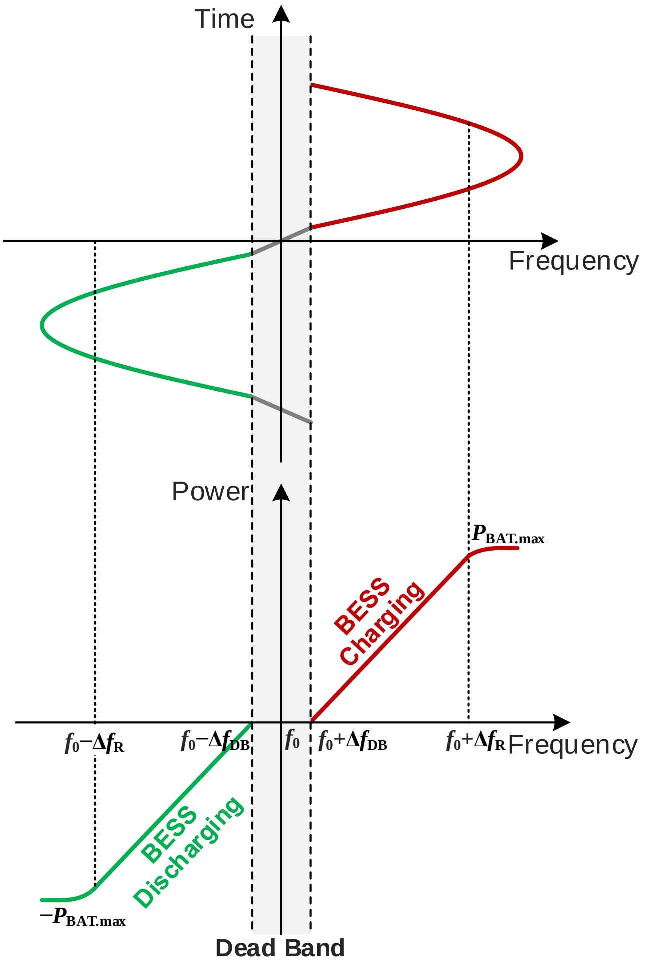

Fig. 3 Power-frequency characteristics of BESS participating in power grid frequency regulation

3.1.2 BESS frequency regulation policy

Guangdong is one of the regions with the most typical market policy of auxiliary service in China. According to the "Guangdong frequency regulation auxiliary service market trading rules" published in Sep. 2020, the economic benefits of frequency regulation can be divided into mileage compensation and capacity compensation. The frequency regulation effect of units is completely reflected by K_f, the comprehensive performance index of the unit in response to the AGC control command. The higher the value of K_f, the better the frequency regulation effect and the higher the economic benefits.

1) Comprehensive performance index K_f

K_f is mainly affected by three key factors: adjustment rate K_1, response time K_2, and adjustment accuracy K_3. Calculation formulas are as follows:

- A*djustment rate* K_1 refers to the rate at which the unit responds to the AGC command, which can be expressed as:

$$K_1=\frac{\left|P(t_1)-P(t_0)\right|}{V_{\mathrm{R}}(t_1-t_0)} \quad (8)$$

where t_0 and t_1 are the start and end times of the adjustment rate calculation period, and V_R is the average standard adjustment rate (p.u.) in the frequency regulation resources distribution area.

- *Response time* K_2 refers to the time delay for the unit to respond to the AGC command, which can be expressed as:

$$K_2 = 1 - \frac{\left|t_{\mathrm{ACT}} - t_{\mathrm{COM}}\right|}{t_{\mathrm{DELI}}} \quad (9)$$

where t_{COM} and t_{ACT} are the command dispatch time and the unit action time respectively, and t_{DELI} is the allowable delay time, which is usually 5 min.

- *Adjustment accuracy* K_3 refers to the accuracy of the unit response to the AGC command, which can be expressed as:

$$K_3 = 1 - \frac{\int_{t_{\mathrm{DB0}}}^{t_{\mathrm{DB1}}} \left|P(t) - P_{\mathrm{AGC}}(t)\right|}{\Delta P_{\mathrm{R}}(t_{\mathrm{DB1}} - t_{\mathrm{DB0}})} \quad (10)$$

where t_{DB0} and t_{DB1} are the start and end time within the target output dead-band respectively, P_{AGC} is the AGC command value, and ΔP_{R} is the allowable adjustment accuracy error.

K_f is used to measure the comprehensive performance of the unit in response to the AGC command, and the calculation formula is as follows:

$$K_f = \lambda_1 \times K_1 + \lambda_2 \times K_2 + \lambda_3 \times K_3 \quad (11)$$

where λ_1, λ_2, and λ_3 are weighting coefficients.

2) Frequency regulation economic revenues

The economic revenues of frequency regulation are composed of mileage compensation R_{MIL} and capacity compensation R_{CAP}.

- *Frequency regulation mileage compensation*

Frequency regulation mileage refers to the absolute value of the difference between the actual output of the generator after the response of one AGC command and the initial output. Mileage compensation is the larger part of the frequency regulation revenues, which is calculated daily and settled monthly. The calculation formulas of *i*-th trading period mileage compensation R_{MIL}^i and the discounted *j*-th monthly total revenues $R_{\mathrm{MIL.PV}}^j$ are as follows:

$$R_{\mathrm{MIL}}^i = \begin{cases} D^i \times Q^i \times \sqrt[m+1]{K_f^i}, & K_f^i \geq 1 \\ D^i \times Q^i \times K_f^i, & K_f^i < 1 \end{cases} \quad (12)$$

$$R_{\mathrm{MIL.PV}}^j = \sum_{i=1}^{T_{\mathrm{MON}}} R_{\mathrm{MIL}}^i (1 + r/12)^{-m} \quad (13)$$

where m is the number of years after the policy is published, and we assume that the policy published year is the same as the BESS commissioning year. From Eq. (12)-(13) we can find that with the increase of years since K_f is squared to the $(m+1)$th power and the revenues are discounted meanwhile, the mileage compensation revenues will decrease rapidly.

- *Frequency regulation capacity compensation*

The AGC capacity is the sum of the upward and downward adjustable capacity within 5 minutes under the current output power of the generating unit. The calculation formula for the discounted j-th monthly capacity compensation $R^j_{\mathrm{CAP.PV}}$ is as follows:

$$R^j_{\mathrm{CAP.PV}} = \sum_{i=1}^{T_{\mathrm{MON}}} C^i \times T^i \times s^i (1+r/12)^{-m} \quad (14)$$

3) Frequency regulation economic costs

The economic costs of frequency regulation mainly consist of two parts: penalty cost C_{PEN} and purchase cost C_{BUY}.

- *Frequency regulation penalty cost*

It should be noted that if BESS cannot provide the required power, it will be punished according to the deviation between the actual power provided and the demand power. The discounted j-th monthly penalty cost $C^j_{\mathrm{PEN.PV}}$ is calculated as follows:

$$C^j_{\mathrm{PEN.PV}} = \sum_{i=1}^{T_{\mathrm{MON}}} \Delta P^i \times T^i \times {\rho_{\mathrm{PEN}}}^i (1+r/12)^{-m} \quad (15)$$

- *Frequency regulation purchase cost*

To satisfy the constraint of SOC value and ensure a certain frequency regulation capability, BESS purchases electricity from the power grid. The discounted j-th monthly electricity purchase cost $C^j_{\mathrm{BUY.PV}}$ is calculated as follows:

$$C^j_{\mathrm{BUY.PV}} = \sum_{i=1}^{T_{\mathrm{MON}}} E^i_{\mathrm{BUY}} \times \rho^i_{\mathrm{BUY}} (1+r/12)^{-m} \quad (16)$$

3.2 Energy time-shift arbitrage service

According to “Guangdong Province Electricity Market Settlement Implementation Rules (Revised Edition)”, in the time-shift arbitrage market, one BESS participates in transactions as both buyer and seller at the same time: it sells electricity at peak prices and purchases electricity at low prices to supplement energy. Unlike frequency regulation service, when participating in time-shift arbitrage, BESS will consistently charge/discharge for a long period. The economic benefits of the discounted j-th monthly energy time-shift arbitrage $R^j_{\mathrm{ARB.PV}}$ is specifically calculated as follows:

$$R_{\mathrm{ARB.PV}}^{j}=\sum_{i=1}^{T_{\mathrm{MON}}}\left(P_{\mathrm{DIS}}^{i}\times T^{i}\times\rho_{\mathrm{PEAK}}^{i}-P_{\mathrm{CHA}}^{i}\times T^{i}\times\rho_{\mathrm{VALL}}^{i}\right)(1+r/12)^{-m} \quad (17)$$

4. BESS whole-life-cycle multi-services planning

4.1 Cycle-life opportunity benefit

The battery life degradation is regarded as a constraint of the benefit maximizing objective function in the previous research, however, there is a one-to-one correspondence between them essentially. Take a simplified single discharge process as an example. The n-th discharge process benefits R^n can be defined as the product of the discharged electricity and unit-price ρ, which can be obtained as:

$$R^n = P_{\mathrm{DIS}}^n \times T^n \times \rho \quad (18)$$

According to Eq. (3), the n-th discharge process life degradation $\mathrm{d}\Gamma^n$ is obtained as:

$$\mathrm{d}\Gamma^n = \frac{d_{\mathrm{eff}}^n}{\Gamma_{\mathrm{R}}} = \frac{\left(\frac{D_A}{D_R}\right)^{\mu_0} \times e^{\mu_1\left(\frac{D_A}{D_R}-1\right)} \times \left(\frac{C_R}{C_A}\right)^{v_0} \times e^{v_1\left(\frac{C_R}{C_A}-1\right)} d_{\mathrm{actual}}}{N_{\mathrm{R}} D_{\mathrm{R}} C_{\mathrm{R}}} \quad (19)$$

where D_{A} can be expressed as follows:

$$D_A = P_{\mathrm{DIS}}^n T^n \big/ C_{\mathrm{BAT.max}} \quad (20)$$

Substituting Eq. (18) & (20) into Eq. (19) and simplifying the obtained equation:

$$\mathrm{d}\Gamma^n = \beta_1 \times (R^n)^{\mu_0+1} \times e^{(\beta_2 \times R^n - \mu_1)} \quad (21)$$

After taking the logarithm on both sides of Eq. (21), the derivative can be obtained as follows:

$$\frac{\mathrm{d}(R^n)}{\mathrm{d}(\mathrm{d}\Gamma^n)} = \frac{R^n}{\mathrm{d}\Gamma^n(\mu_0 + 1 + \beta_2 R^n)} \geq 0 \quad (22)$$

where β_1 and β_2 are constant coefficients, greater than 0, and simplified from the known variables in Eq. (18)-(20). From Eq. (22) we can find that there is a strict one-to-one correspondence between R and $\mathrm{d}\Gamma$. Since the life degradation model is discrete, rated life Γ_{R} can be split into a finite number of cycle-life scales $\mathrm{d}\Gamma$. In order to maximize the overall benefits, the benefits in each $\mathrm{d}\Gamma$ should be maximized.

To avoid the impact of $\mathrm{d}\Gamma$ difference on the calculation of different service benefits, we define the concept of cycle-life opportunity benefit $\mathrm{d}R$, the ratio of the benefits R to cycle-life scale $\mathrm{d}\Gamma$:

$$\mathrm{d}R = R / \mathrm{d}\Gamma \quad (23)$$

which can be considered as the benefit of selecting one service while giving up all other services under the premise of consuming the unit battery cycle life. The larger $\mathrm{d}R$ obtained, the higher benefits can be achieved in the unit cycle life. When BESS is applied in the electricity market, $\mathrm{d}R$ of multiple services are different and time-variant. For the purpose of the maximization of the overall benefits throughout the whole life cycle, the application is always switched to the service with the highest $\mathrm{d}R$ based on the $\mathrm{d}R$ re-evaluation of all the available services in the next $\mathrm{d}\Gamma$. Take the services of frequency regulation and time-shift arbitrage in the BESS whole-life-cycle optimal planning as an example, at the first life segment, BESS is applied in frequency regulation due to the highest dR, which is beneficial to rapidly recover investment costs. As the years grow, the benefits of frequency regulation decrease sharply as shown in Eq. (12)-(13), the application should be switched to time-shift arbitrage once its dR is higher than that of the frequency regulation.

4.2 Overview of whole-life-cycle multi-services planning

When BESS is applied to a variety of available services, the overview of the planning is presented as shown in Fig. 4: At the beginning of the planning, the BESS cycle-life degradation is 0. The BESS's owner calculates the cycle-life opportunity benefits dR of the different available services and selects the highest one as the application in the first life segment. And then, the cycle-life opportunity benefits dR are re-calculated in each cycle-life scale dΓ, and the application will be switched to another service for the next life segment once the current service is not the one with the highest cycle-life opportunity benefit. The length of the cycle-life scale dΓ will be adjusted dynamically if the differences in the cycle-life opportunity benefits dR between the current service and the other services have been changed.

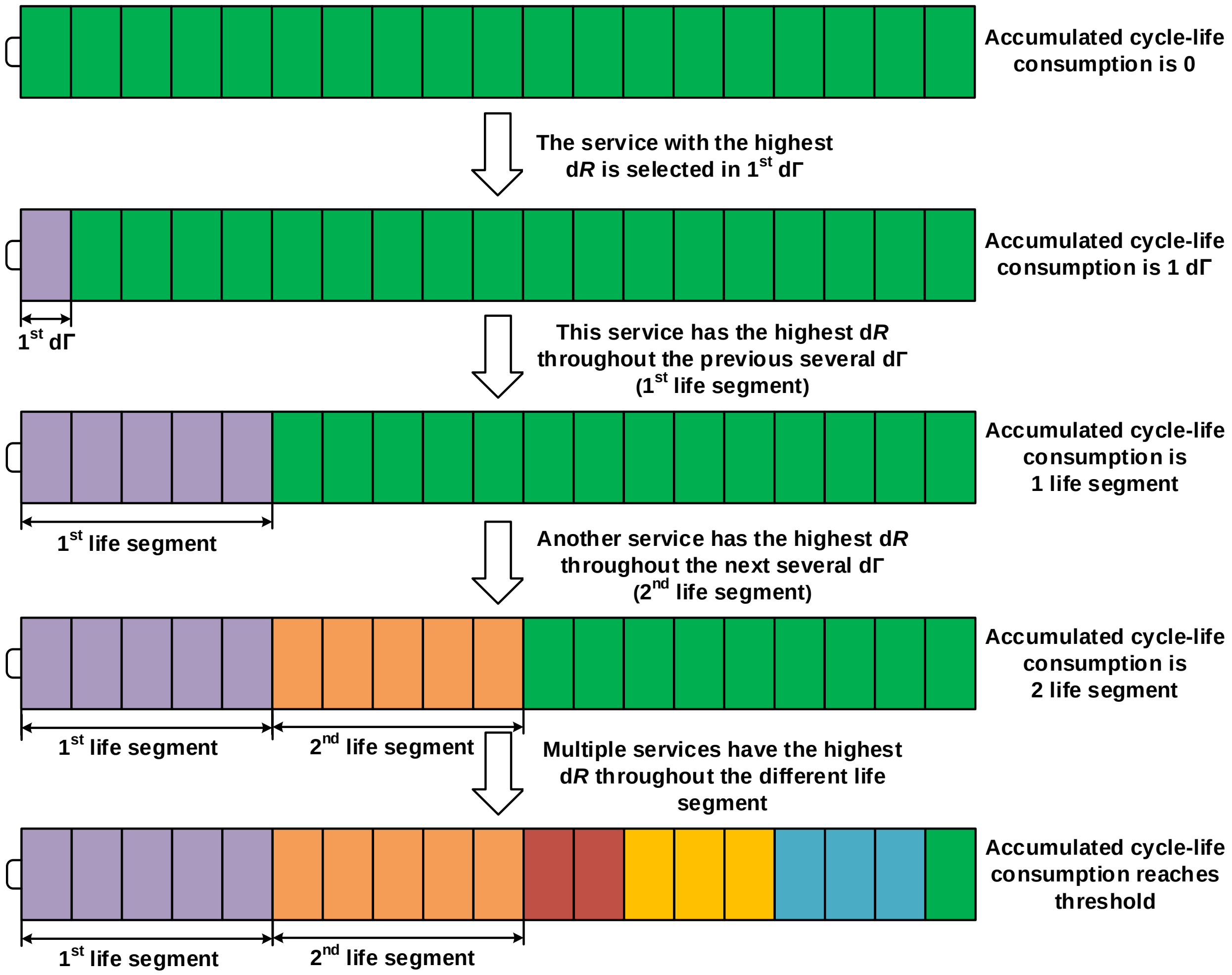

Fig. 4 The framework of the proposed multi-services planning

It should be noticed that: 1) The concepts of cycle life scale and life segment are different. The cycle life scale refers to the computational time scale of the planning, and if the applied services are the same in consecutive multiple cycle life scales, these cycle life scales will together constitute one life segment; 2) BESS can be flexibly switched among different services, the only criterion is the service's profitability index, i.e. the cycle life opportunity benefit, thus there may be multiple life segments; 3) Due to the increase in battery internal resistance and the consequent heat loss, the actual service life is always less than the rated life, and once the degraded cycle-life of the BESS reaches the threshold (80% in this article), BESS will be forced to scrap; 4) The value of the cycle-life scale $d\Gamma$ is not constant and it can be dynamically adjusted according to the current value of different application services dR, a detailed introduction is as shown in Eq. (37).

4.3 Specific steps of multi-services planning

The solution procedures of the proposed multi-services planning are as follows:

```
Algorithm: Solution for the BESS multi-services planning in whole-life-cycle
Initialization: Battery parameters, available services parameters, cycle-life scale, number of life segment $l$=0, etc.
For (number of cycle-life scale $k$=1:$k_{\max}$) do:
    for (multiple available services $p$=1:$P$) do:
        Calculate the $k$-th scale cycle-life opportunity benefit $dR_{(k)}$ of service $p$ (for example Eq. (25), (26))
    end
    The service with the highest $dR_{(k)}$ is selected as the application in the $k$-th cycle-life scale (for example Eq. (32))
    Calculate the present value $R_{\mathrm{PV}(k)}$ of the economic profit in the $k$-th cycle-life scale (for example Eq. (33))
    if $R_{\mathrm{PV}(k)}<0$ or accumulated cycle-life consumption reaches 80%
        break
    end
    if (service in the $k$-th scale) ≠ (service in the ($k$-1)-th scale)
        $l = l+1$
    end
    Calculate the value of the cycle-life scale dynamically (A detailed introduction is shown in Eq. (37))
End
Calculate the NPV of the total benefits $R_{\mathrm{NPV}}$(for example Eq. (38))
Output final solution
```

As the typical services in the electricity market, frequency regulation and time-shift arbitrage are selected as two BESS available services to introduce the details of the proposed planning. Fig. 5 shows the specific implementation steps, which are introduced as follows:

Step 1: Set the number of cycle-life scales k=1.

Step 2: Given the $d\Gamma$ initial value $d\Gamma_{(0)}$, determine the value of $d\Gamma_{(\mathrm{k})}$, as shown below:

$$d\Gamma_{(k)} = \max\left\{d\Gamma_{(0)}, d\Gamma_{\mathrm{FRE}(k)}, d\Gamma_{\mathrm{ARB}(k)}\right\} \quad (24)$$

where $\mathrm{d}\Gamma_{\mathrm{FRE}(k)}$ and $\mathrm{d}\Gamma_{\mathrm{ARB}(k)}$ represent the degraded cycle-life within one day of the frequency regulation and time-shift arbitrage respectively, which is used to avoid that $\mathrm{d}\Gamma$ is so small that BESS' owner frequently switches application services in one day.

Step 3: Calculate the cycle-life opportunity benefits $\mathrm{d}R_{(k)}$ of two services:

1) Frequency regulation cycle-life opportunity benefit $\mathrm{d}R_{\mathrm{FRE}(k)}$:

$$\mathrm{d}R_{\mathrm{FRE}(k)}=R_{\mathrm{FRE.PV}(k)}/\mathrm{d}\Gamma_{(k)}=\frac{R_{\mathrm{MIL.PV}(k)}+R_{\mathrm{CAP.PV}(k)}-C_{\mathrm{PEN.PV}(k)}-C_{\mathrm{BUY.PV}(k)}}{\mathrm{d}\Gamma_{(k)}} \quad (25)$$

2) Time-shift arbitrage cycle-life opportunity benefit $\mathrm{d}R_{\mathrm{ARB}(k)}$:

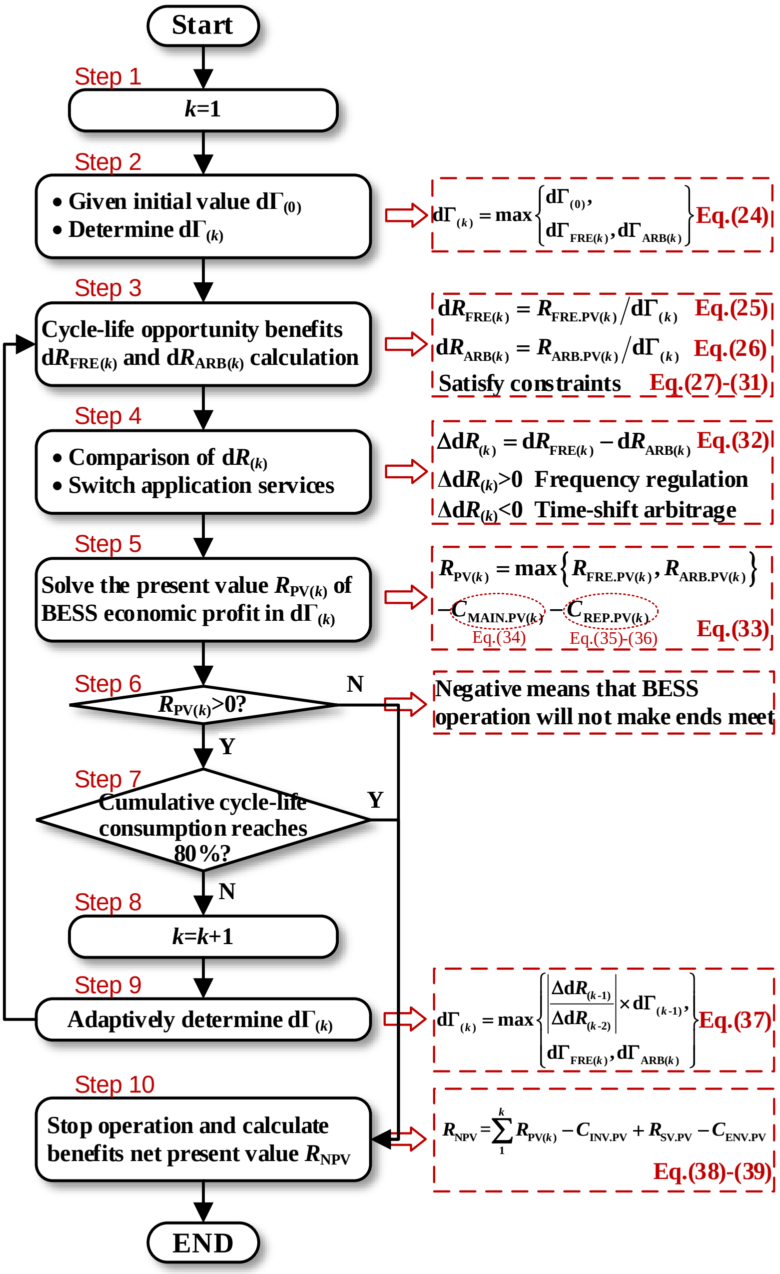

Fig. 5 The specific implementation steps of the proposed planning

$$\mathrm{d}R_{\mathrm{ARB}(k)} = R_{\mathrm{ARB.PV}(k)} / \mathrm{d}\Gamma_{(k)} \quad (26)$$

The following constraints need to be met at all times during the BESS operation process:

Power constraints:

$$0 \le P_{\mathrm{CHA}}(t) \le P_{\mathrm{BAT.max}}; -P_{\mathrm{BAT.max}} \le P_{\mathrm{DIS}}(t) \le 0 \quad (27)$$

SOC constraints:

$$C_{\mathrm{BAT}}(t) = (1-\delta) C_{\mathrm{BAT}}(t-1) + \left(P_{\mathrm{CHA}}(t)\theta_{\mathrm{CHA}} - P_{\mathrm{DIS}}(t)/\theta_{\mathrm{DIS}}\right)\Delta t \quad (28)$$

$$SOC_{\mathrm{BAT}}(t) = C_{\mathrm{BAT}}(t) / C_{\mathrm{BAT.max}}(t) \quad (29)$$

$$SOC_{\mathrm{BAT.min}} \le SOC_{\mathrm{BAT}}(t) \le SOC_{\mathrm{BAT.max}} \quad (30)$$

$$SOC_{\mathrm{BAT.start}} = SOC_{\mathrm{BAT.end}} = SOC_{\mathrm{BAT.set}} \quad (31)$$

where $SOC_{\mathrm{BAT.start}}$ and $SOC_{\mathrm{BAT.end}}$ are the start and end values of SOC within a day, which should be equal to the given value $SOC_{\mathrm{BAT.set}}$.

Step 4: Compare the value of $\mathrm{d}R_{\mathrm{FRE}(k)}$ and $\mathrm{d}R_{\mathrm{ARB}(k)}$, and calculate the difference between $\mathrm{d}R_{\mathrm{FRE}(k)}$ and $\mathrm{d}R_{\mathrm{ARB}(k)}$, which is defined as $\Delta\mathrm{d}R_{(k)}$:

$$\Delta\mathrm{d}R_{(k)} = \mathrm{d}R_{\mathrm{FRE}(k)} - \mathrm{d}R_{\mathrm{ARB}(k)} \quad (32)$$

If $\Delta\mathrm{d}R_{(k)} > 0$, that is, $\mathrm{d}R_{\mathrm{FRE}(k)} > \mathrm{d}R_{\mathrm{ARB}(k)}$, then BESS is applied to frequency regulation during the cycle-life scale of $\mathrm{d}\Gamma_{(k)}$; conversely, BESS is applied to time-shifting arbitrage.

Step 5: Solve the present value $R_{\mathrm{PV}(k)}$ of the economic profit of BESS in the cycle-life scale of $\mathrm{d}\Gamma_{(k)}$. In order to guarantee BESS's continuous reliability, maintenance and replacement are needed periodically, thus $R_{\mathrm{PV}(k)}$ can be obtained by subtracting the operation & maintenance cost and the battery replacement cost from the maximum benefits obtained in the actual application services:

$$R_{\mathrm{PV}(k)} = \max\left\{R_{\mathrm{FRE.PV}(k)}, R_{\mathrm{ARB.PV}(k)}\right\} - C_{\mathrm{MAIN.PV}(k)} - C_{\mathrm{REP.PV}(k)} \quad (33)$$

To be consistent with the above settlement time-scale in the electricity market, the calculation formula for the discounted j-th monthly operation & maintenance cost $C^{j}_{\mathrm{MAIN.PV}}$ is as follows:

$$C^{j}_{\mathrm{MAIN.PV}} = \sum_{i=1}^{T_{\mathrm{MON}}} P^{i}_{\mathrm{BAT.max}} \times \rho_{\mathrm{MAIN}} (1 + r/12)^{-m} \quad (34)$$

The discounted j-th monthly battery replacement cost $C^{j}_{\mathrm{REP.PV}}$ is calculated as follows:

$$C^{j}_{\mathrm{REP.PV}} = \sum_{N_{\mathrm{REP}}=1}^{N_{\mathrm{REP.max}}} C_{\mathrm{BAT.max}} \times \rho_{\mathrm{REP}} (1 + r/12)^{-mN_{\mathrm{REP}}/(N_{\mathrm{REP.max}}+1)} \quad (35)$$

where $N_{\mathrm{REP.max}}$ is the total number of battery replacements, as shown below:

$$N_{\mathrm{REP.max}} = m/m_{\mathrm{CAL}} - 1 \quad (36)$$

Step 6: Determine the positive or negative of $R_{\mathrm{PV}(k)}$. If negative, it means that BESS will be unable to make ends meet on the current $\mathrm{d}\Gamma_{(k)}$ scale. Continued utilization of BESS can only lead to a decrease in overall benefits. BESS operation should be terminated and the algorithm goes to **Step 10**; Otherwise, continue to execute the algorithm.

Step 7: Judge whether the accumulated cycle-life consumption reaches 80%. If it has reached 80%, the BESS operation should be terminated and the algorithm goes to **Step 10**; Otherwise, continue to execute the algorithm.

Step 8: Set the number of cycle-life scale $k=k+1$.

Step 9: Determine the value of $\mathrm{d}\Gamma_{(k)}$ adaptively, as shown below:

$$\mathrm{d}\Gamma_{(k)} = \max\left\{\left|\frac{\Delta \mathrm{d}R_{(k\text{-}1)}}{\Delta \mathrm{d}R_{(k\text{-}2)}}\right| \times \mathrm{d}\Gamma_{(k\text{-}1)}, \mathrm{d}\Gamma_{\mathrm{FRE}(k)}, \mathrm{d}\Gamma_{\mathrm{ARB}(k)}\right\} \quad (37)$$

where the value of k-th cycle-life scale $\mathrm{d}\Gamma_{(k)}$ is dynamically predicted by the trend changes of $\Delta \mathrm{d}R$ in the front two scales of (k-1) and (k-2). When $\Delta \mathrm{d}R$ increases, we consider that the two services will not be switched in a short time. Therefore, $\mathrm{d}\Gamma$ is adaptively increased to reduce the calculation amount. When $\Delta \mathrm{d}R$ continuously decreases, we consider that the two services will be switched soon, so $\mathrm{d}\Gamma$ is adaptively decreased to improve the calculation accuracy.

Go to **Step 3** to continue execution.

Step 10: Terminate the utilization of BESS, the NPV of the total benefits R_{NPV} can be calculated as:

$$R_{\mathrm{NPV}} = \sum_{1}^{k} R_{\mathrm{PV}(k)} - C_{\mathrm{INV.PV}} + R_{\mathrm{SV.PV}} - C_{\mathrm{ENV.PV}} \quad (38)$$

where $C_{\mathrm{INV.PV}}$ is the initial investment cost, $R_{\mathrm{SV.PV}}$ is the residual value of the equipment and $C_{\mathrm{ENV.PV}}$ is the environmental recovery cost. The initial investment cost includes power cost and capacity cost, and the specific expression is as follows:

$$C_{\mathrm{INV.PV}} = \rho_{\mathrm{P}} P_{\mathrm{BAT.max}} + \rho_{\mathrm{C}} C_{\mathrm{BAT.max}} \quad (39)$$

It should be noted that the recycling technology of lithium iron phosphate batteries is complex and costly. There is currently no good recycling plan and specific recycling value. The residual value can be regarded as 0 approximately. Currently, there are no exact data references for the environmental protection expenses caused by battery recycling, which will not be considered temporarily.

5. Case studies: different BESS planning schemes

5.1 Parameter settings

5.1.1 Battery noumenon parameters

The tested battery is a lithium iron phosphate battery. The rated power capacity $P_{\text{BAT.max}}$ is selected as 1 MW, which is approximately equal to the maximum power required for frequency regulation in electricity market history (Wali et al, 2022). According to the convention, the full power charge and discharge energy for 2 hours is used as the rated energy capacity, $C_{\text{BAT.max}}$ is 2 MWh. Table 1 lists the technical and economic parameters used in different application services. And the calendar life of the traditional BESS is generally 15~20 years, but the BESS currently in operation has the ability to provide the services for around 30 years (Colthorpe, 2020). With the continuous innovation of materials and the intelligent development of control, the expected calendar life of the BESS will also be extended. Therefore, the calendar life limit is assumed as 30 years in this paper.

Table 1 Battery technical and economic parameters

Parameter name	**Corresponding symbol**	**Parameter value**
Battery cycle-life degradation model parameters		
Rated DOD	D_R	0.5
Rated cycles	N_R	2500
Life cycle curve fitting parameters	μ_0, μ_1	0.19, 1.69
Effective discharge fitting parameters	v_0, v_1	1, 0
Polynomial fitting parameters	a_0, a_1, a_2	72.1360, 0.2597, 0.0023
Battery operating constraint parameters		
SOC upper and lower limit	$SOC_{\text{BAT.min}}$, $SOC_{\text{BAT.max}}$	0.2, 0.8
SOC initial value	$SOC_{\text{BAT.set}}$	0.5
Self-discharge rate	δ	0.24%
Round-trip efficiency	$\theta_{\text{CHA}}/\theta_{\text{DIS}}$	0.75
Economic parameters		
Operation & maintenance cost	ρ_{MAIN}	120 CNY/MW/day
The construction cost	ρ_P	200000 CNY/MW
The construction cost	ρ_C	400000 CNY/MWh
Calendar life limit	m_{CAL}	30 years
Discount rate	r	5%

5.1.2 Application services parameters

When BESS participates in the frequency regulation auxiliary service, the typical daily AGC signal of four seasons issued by the dispatch center is shown in Fig. 6.

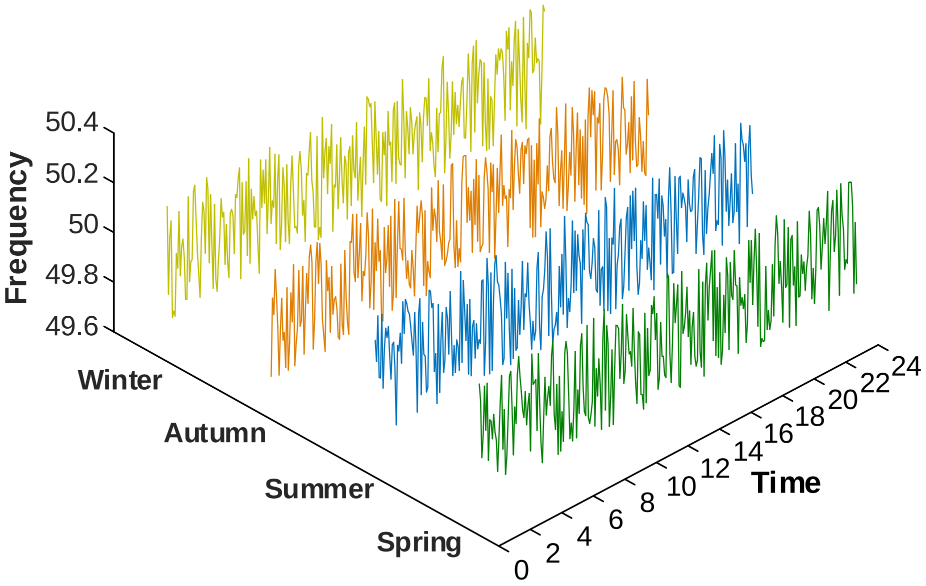

Fig. 6 The given BESS frequency regulation signal

According to the "Guangdong frequency regulation auxiliary service market trading rules", the weight coefficients in the comprehensive performance index K_f of Guangdong Province frequency regulation auxiliary service market are: $\lambda_1 = 0.5$, $\lambda_2 = 0.25$, $\lambda_3 = 0.25$, and the unit AGC capacity compensation s is 3.56 CNY/MWh. BESS can achieve the seconds level response and can accurately control the output power, so the K_f value of BESS is much higher than K_f values of other conventional units that participated in frequency regulation. However, in order to protect the interests of conventional units, the electricity market operator set the K_f value of BESS as the highest K_f value of conventional units in a frequency regulation resources distribution area. Referring to the operation data of the best performing thermal unit in Guangdong (Chen et al, 2021), combined with Eq. (8)-(10), K_1=4.10, K_2=0.94, K_3=0.96 can be calculated, and K_f=2.53 can be calculated from Eq. (11).

The calculation formula of the settlement price is as follows: settlement price = quoted price of the last bid-winning unit/ (K_f value of this unit / K_f value of the best performing unit). To win the bid, the low-performance units will be quoted as low as possible. We assume that quoted price of the last bid-winning unit is the lower limit of the declared price allowed by the market $Q_{\min}$= 5.50 CNY/MW. In the current Guangdong frequency regulation market, the most participant is coal-fueled thermal generators combined with BESS, we conservatively estimated that the K_f value of the last bid-winning unit is 1.28 (Xie et al, 2021), so the actual settlement price Q=10.87 CNY/MW.

When BESS participates in time-shift arbitrage, the same charge/discharge strategy is selected (Zhang et al, 2020) to facilitate the comparison of the planning results. Assuming that the BESS is fully charged and discharged once a day, it is charged during the valley period of electricity price from 2:00 to 7:00 am, and discharged during the peak period of electricity price from 5:00 to 10:00 pm. The electricity prices during the peak, flat and valley periods are 600.00, 425.00, and 250.00 CNY/MWh respectively.

5.2 Case studies results

5.2.1 Proposed planning results analysis

The change of BESS benefits NPV over time in the whole life cycle is shown in Fig. 7 and Table 2. Each discrete point represents a simulation result in cycle-life scale $\mathrm{d}\Gamma$, and $\mathrm{d}\Gamma_{(0)}$ is taken as 0.005. The density of points reflects the change in the cycle-life scale. Fig. 7 also shows the NPV of benefits for frequency regulation and time-shift arbitrage in the whole life cycle.

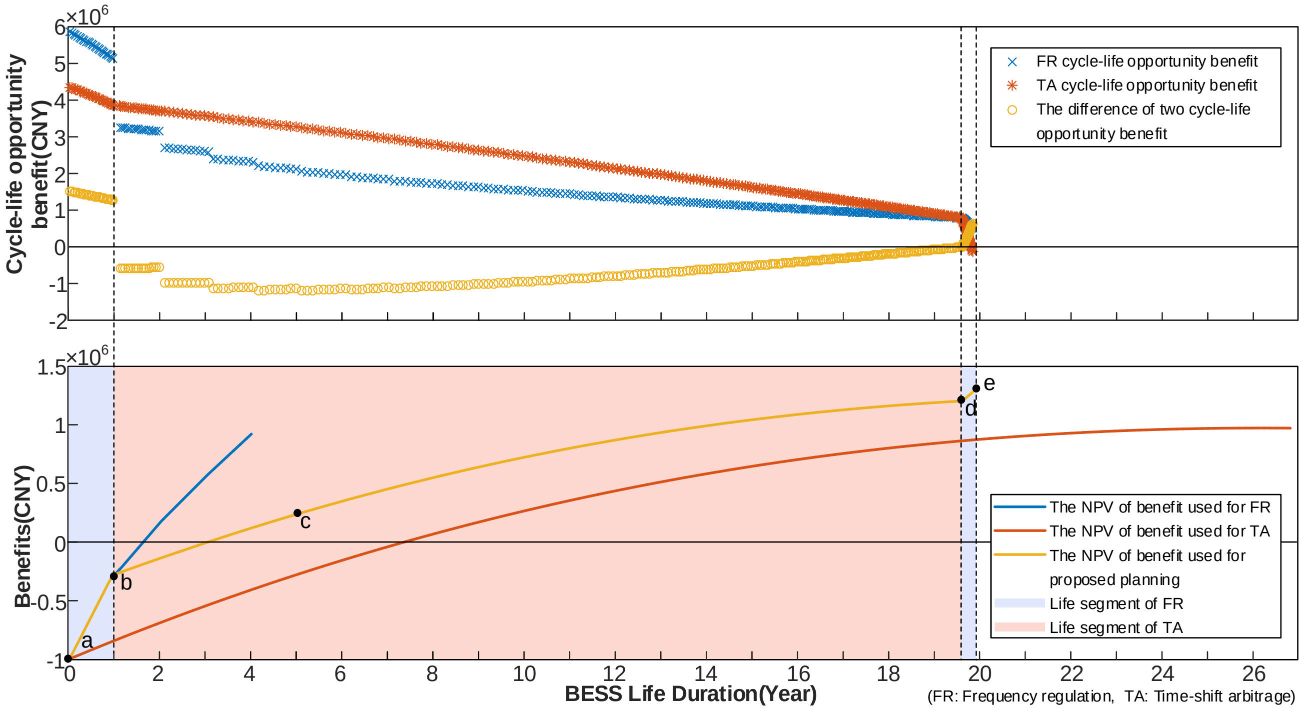

Fig. 7 The NPV of benefit used solely for frequency regulation, time-shift arbitrage, and the proposed planning

Table 2 Changes in the benefit NPV of the proposed planning over time

Life segment	**1st life segment (a-b)**	**2nd life segment (b-d)**	**3rd life segment (d-e)**
Duration (year)	0~1.00	1.00~19.61	19.61~19.85
Application services	Frequency regulation	Time-shift arbitrage	Frequency regulation
Accrued benefits NPV (CNY)	-285709.00	1209595.96	1277777.78

From the results, we can draw the following conclusions:

1) The payback period of the whole BESS project is about 3.12 years, and the battery lifespan is about 19.85 years;

2) In the **1st life segment a-b**, the initial period of operation (within one year), $\Delta \mathrm{d}R$ is always greater than 0, which means $\mathrm{d}R_{\mathrm{FRE}}$ is greater than $\mathrm{d}R_{\mathrm{ARB}}$. BESS is applied to frequency regulation. The value of $\mathrm{d}\Gamma$ is becoming smaller (the density of points increases from **a** to **b**) with the decrease of the $|\Delta \mathrm{d}R|$.

3) In the **2nd life segment b-d**, after one year of frequency regulation service, the revenue will drop sharply as shown in Eq. (12). $\Delta \mathrm{d}R$ is always less than 0, which means $\mathrm{d}R_{\mathrm{FRE}}$ is less than $\mathrm{d}R_{\mathrm{ARB}}$, so BESS service changes from the frequency regulation to time-shift arbitrage in the second year. The value of $\mathrm{d}\Gamma$ is becoming smaller (the density of points increases) with the slight decrease of the $|\Delta \mathrm{d}R|$. It can be predicted that if $|\Delta \mathrm{d}R|$ decreasing continues, $\mathrm{d}R_{\mathrm{FRE}}$ will be greater than $\mathrm{d}R_{\mathrm{ARB}}$, and BESS will be applied to frequency regulation again. However, when the third year arrives, frequency regulation revenue is in a sharp decline. Therefore, BESS will be kept to provide the time-shift arbitrage service for a long period. Although $\mathrm{d}R_{\mathrm{FRE}}$ is still smaller than $\mathrm{d}R_{\mathrm{ARB}}$, the $|\Delta \mathrm{d}R|$ is constantly decreasing in the later period (**c-d**), so the value of $\mathrm{d}\Gamma$ is becoming smaller (the density of points increases from **c** to **d**). There is a high possibility of BESS being re-applied to frequency regulation service.

4) In the **3rd life segment d-e**, the last period of operation, $\mathrm{d}R_{\mathrm{FRE}}$ overtakes $\mathrm{d}R_{\mathrm{ARB}}$, and BESS is re-applied to frequency regulation and is immediately scrapped. Due to the decay of battery cycle-life, the energy capacity is far smaller than the rated energy capacity, and the quantity of electricity that can be charged/ discharged in one day is so small that the time-shift arbitrage revenue $R_{\mathrm{ARB.PV}}$ is extremely low. When $R_{\mathrm{ARB.PV}}$ is less than the operation & maintenance cost $C_{\mathrm{MAIN.PV}}$, the NPV of overall benefits R_{NPV} even decreases slightly, as shown in the time-shift arbitrage benefit NPV curve. The battery energy capacity can still meet single or several commands of frequency regulation. Although BESS needs to purchase electricity from the grid frequently and faces the prospect of more power-shortage penalty, frequency regulation revenue $R_{\mathrm{FRE.PV}}$ is still profitable, so BESS is applied to frequency regulation again.

5.2.2 Case studies results comparison

From Fig. 7 and Table 2, we preliminarily conclude that the proposed planning can maintain a balance of prolonging the BESS operation lifespan and shortening the payback period, and can achieve higher benefits NPV than participating in frequency regulation or time-shift arbitrage alone. To further verify the superiority of the proposed planning, the tests of the five different BESS service planning schemes are implemented. Table 3 lists the comparison of results and benefits under the five cases in detail.

Case I: BESS for frequency regulation utilization only;

Case II: BESS for time-shift arbitrage utilization only;

Case III: BESS for stacked service (frequency regulation and time-shift arbitrage simultaneously), calculated from the scheme presented in (Shi et al, 2018);

Case IV: BESS for successive service (frequency regulation and time-shift arbitrage successively), calculated from the whole-life-cycle planning scheme presented in (Zhang et al, 2020);

Case V: BESS adopts the proposed planning to flexibly participate in frequency regulation and time-shift arbitrage.

It can be found from the results of the five cases in Table 3:

Table 3 Comparison of BESS planning results under different utilization cases

	Case I	**Case II**	**Case III**	**Case IV**	**Case V**	**Comparison**
Frequency regulation	√		√	√	√	
Time-shift arbitrage		√	√	√	√	
Services sequence	Individual	Individual	Simultaneous	Successive	Flexible	
Investment payback period (year)	1.66	7.42	2.04	3.12	3.12	I<III<V=IV<II
Frequency regulation duration (year)	4.03	0	3.33	1.00	1.23	
Time-shift arbitrage duration (year)	0	26.83	3.33	23.17	18.62	
Lifespan (year)	4.03	26.83	3.33	24.17	19.85	III<I<V<IV<II
Frequency regulation benefits (CNY)	1913067.75	0	1221538.90	714291.00	782472.82	
Time-shift arbitrage benefits (CNY)	0	1948059.57	314311.17	1414594.38	1495304.96	
Benefits NPV(CNY)	**913067.75**	**948059.57**	**535850.07**	**1128885.38**	**1277777.78**	**III<I<II<IV<V**

1) In **Case I**, BESS is only used for frequency regulation service. The cycle-life of BESS decays fast due to frequently high-power charge/discharge, and the lifespan duration is only 4.03 years. The substantial benefits can be obtained in a relatively short period, and the payback period of 1.66 years is the shortest one in all cases. But the battery degradation process is also accelerated, which is not conducive to environmental protection.

2) In **Case II**, BESS is only used for time-shift arbitrage. The cycle-life of BESS decays more slowly due to the daily high-energy charge/discharge, and the lifespan duration is 26.83 years. Although the long-term accumulated NPV of benefit is higher than that of frequency regulation, the payback period of investment is also as long as 7.42 years, which is not expected by investors.

3) In **Case III**, BESS is applied to frequency regulation and time-shift arbitrage simultaneously. Its cycle lifespan duration is the shortest, only 3.33 years. However, accelerated life degradation does not bring super-linear benefits integrating the cycle-life degradation model. On the contrary, the NPV of benefits is even less than that of individual services. The payback period is 2.04 years, which is longer than that of frequency regulation.

4) In **Case IV**, BESS is applied to frequency regulation and time-shift arbitrage successively. BESS is first used for frequency regulation with a duration of 1.00 years. Over certain cycle-life degradation,

BESS is then transferred for time-shift arbitrage with a duration of 23.17 years. The lifespan duration is 24.17 years, which is slightly shorter than Case II, but much longer than Case I. Besides, compared with Case I, Case II, and Case III, the overall benefits increased by 23.6%, 19.1%, and 110.7%.

5) In **Case V**, the proposed planning based on cycle-life opportunity benefit is adopted. The detailed planning results have been analyzed above. The total lifespan duration is 19.85 years, it is much longer than Case I and Case III, which is environment-friendly. And the investment payback period is 3.12 years, which is slightly longer than Case I and Case III, but much shorter than Case II. It can achieve recover initial investment rapidly. Also, compared with the front four cases, the overall benefits of Case V is increased by 39.9%, 34.8%, 138.5%, and 13.2%.

Finally, the comparison among the results of Case III, Case IV, and Case V is required to be further discussed. It is necessary to notice that all the cases are tested under market rules as shown in Section 3. In the initial stage of operation, applying the full capacity of BESS in frequency regulation with the highest cycle-life opportunity benefit is the optimal choice. But in Case III, BESS is used in time-shift arbitrage simultaneously, which reduces the available capacity for frequency regulation. After one year, the optimal choice of the BESS service is time-shift arbitrage individually, but in Case III, BESS is used in frequency regulation simultaneously, which also reduces the available capacity for time-shift arbitrage. Thus, the overall benefits of Case III are the lowest. And in Case IV, BESS is not available to be multiply switched between frequency regulation and time-shift arbitrage, therefore, Case IV has lower overall benefits due to the lack of the revenue of the re-applied frequency regulation service as in Case V.

5.3 Planning sensitivity evaluation to market price signals

In the above analysis, the peak-valley price margin of time-shift arbitrage is given to compare among the different five cases easily. Market price rules always change with government policies, so the sensitivity of market price signals should be an essential characteristic of the proposed planning. To further evaluate the sensitivity of the proposed planning to market price signals, the different peak-valley price margins are considered for providing different solutions in the whole life cycle. Specifically, different price margins are added to Eq. (17) for comparison. The results are shown in Table 4 and Fig. 8, respectively.

It can be found in Table 4 and Fig. 8:

1) As the peak-to-valley price margin decreases, the duration for BESS to participate in the frequency regulation market increases. When the margin decreases to 290 CNY/MWh, BESS will fully participate in the frequency regulation market; Otherwise, as the peak-to-valley price margin increases, the duration for BESS to participate in the time-shift arbitrage market increases. When the margin increases to 450 CNY/MWh, BESS will fully participate in the time-shift arbitrage market.

2) The proposed planning is extremely sensitive to price signals, and the application services can be flexibly switched in response to changes in price signals. In most instances, multi-services BESS could gain higher benefits than individual service.

Table 4 Planning results comparison under different peak-valley price margins

P2VPM (CNY/ MWh)	290	310	330	350 (Case V)	370	390	410	430	450
FR	√	√	√	√	√	√	√	√	
TA		√	√	√	√	√	√	√	√
Segment number	1	5	4	3	3	3	3	3	1
Payback period (year)	1.66	1.66	3.45	3.12	3.04	2.95	2.75	3.08	5.02
FR duration (year)	4.03	2.47	1.32	1.23	1.18	1.11	1.06	1.04	0
TA duration (year)	0	10.93	17.33	18.62	19.62	20.61	21.45	22.08	26.83
Lifespan (year)	4.03	13.40	18.65	19.85	20.80	21.72	22.51	23.12	26.83
FR benefits (CNY)	1913067.75	1308248.52	813909.33	782472.82	754630.48	724571.27	709143.76	686818.57	0
TA benefits (CNY)	0	621040.15	1225976.65	1495304.96	1534019.23	1695507.02	1843053.47	2001962.3	2845566.73
Benefits NPV (CNY)	**913067.75**	**929288.67**	**1039885.98**	**1277777.78**	**1288649.71**	**1420078.29**	**1552197.23**	**1688780.57**	**1845566.73**
Benefits NPV for FR alone (CNY)	**913067.75**	**913067.75**	**913067.75**	**913067.75**	**913067.75**	**913067.75**	**913067.75**	**913067.75**	**913067.75**
Benefits NPV for TA alone (CNY)	**412306.27**	**590890.70**	**769475.14**	**948059.57**	**1126644.00**	**1305228.43**	**1483812.87**	**1662397.30**	**1845566.73**

(P2VPM: peak-valley price margin, FR: Frequency regulation, TA: Time-shift arbitrage)

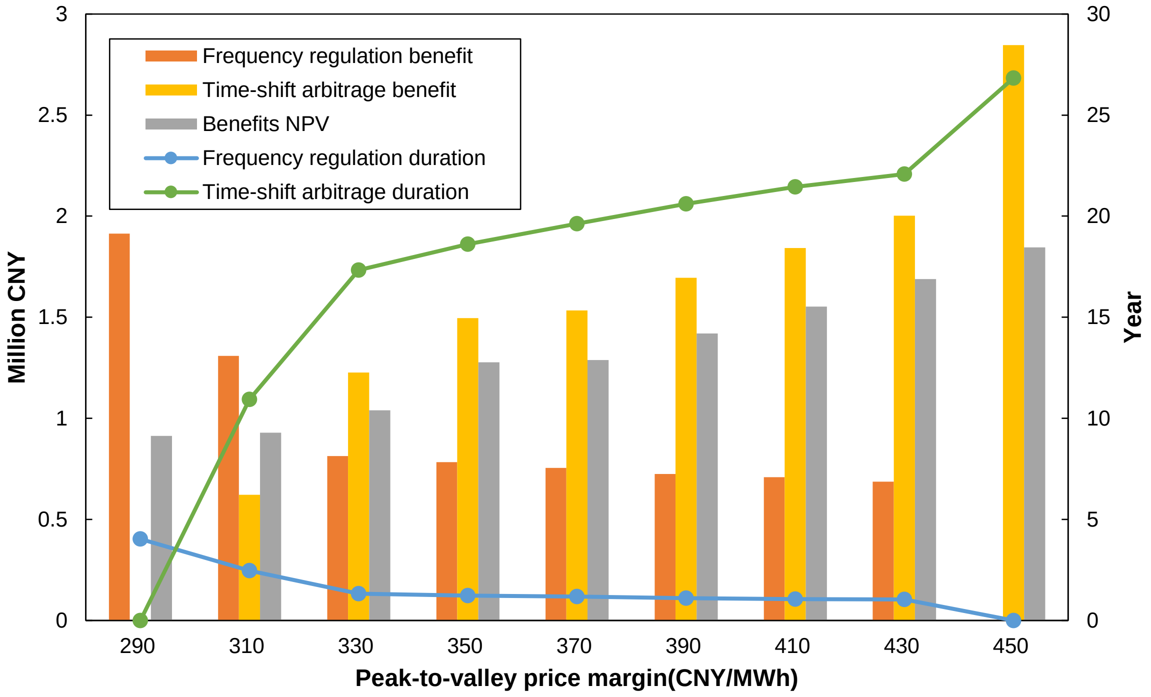

Fig. 8 Comparison of benefits and duration under different peak-valley price margins

3) The most common life segment number is 3, similar to Fig. 7. But the number of life segments increases when the margin is small, which means more frequent switching between the application services. Take the planning result under a price margin of 310 CNY/MWh as an example, we analyze the multi-segment over the whole life cycle in detail. And the changes in the BESS's benefits NPV over time are shown in Table 5 and Fig. 9.

Table 5 Changes of the benefits NPV overtime under the peak-to-valley price margin of 310CNY/MWh

Life segment	**1st life segment**	**2nd life segment**	**3rd life segment**	**4th life segment**	**5th life segment**
Duration (year)	0~1.00	1.00~1.60	1.60~2.00	2.00~15.33	15.33~15.75
Frequency regulation	√		√		√
Time-shift arbitrage		√		√	
Accrued benefits NPV (CNY)	-285709.00	-211967.30	-32360.35	797868.44	929288.67

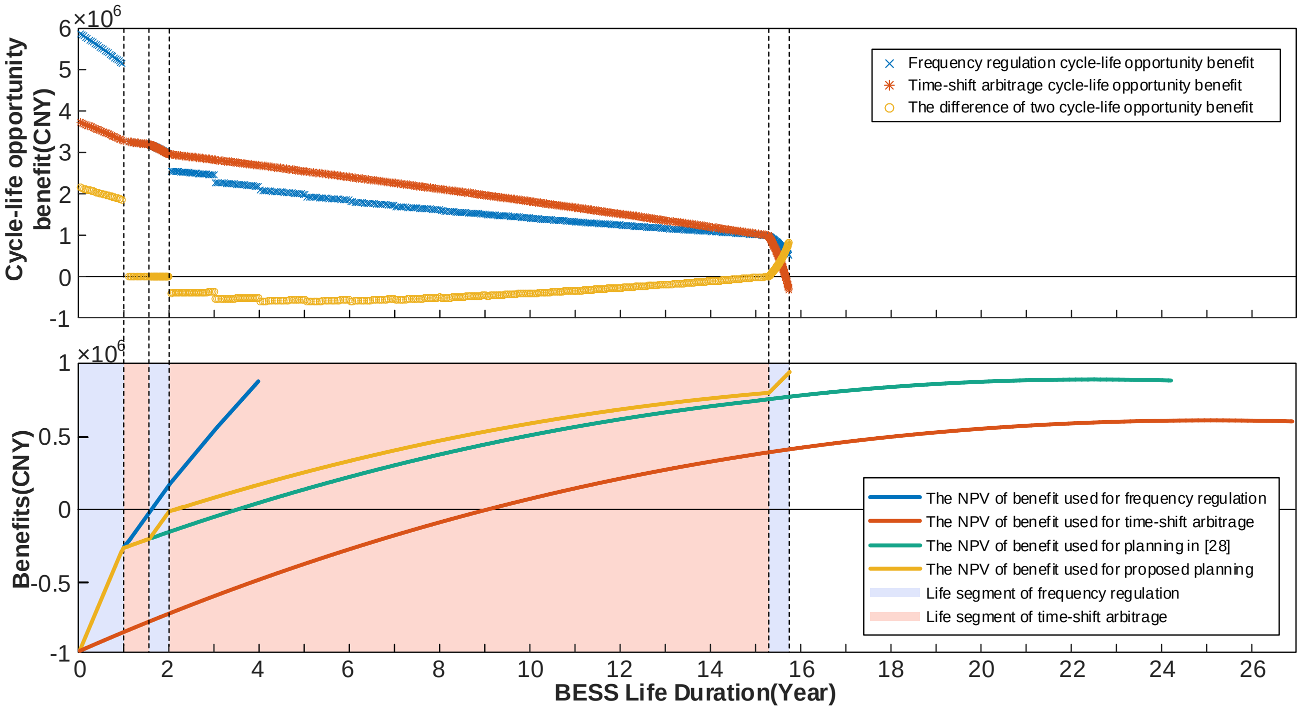

Fig. 9 The NPV of benefits used for the proposed planning under the peak-to-valley price margin of 310 CNY/MWh

From the results, we can find that due to the reduction of the peak-to-valley price margin, the profitability of time-shift arbitrage is not as strong as that shown in Fig. 7. Therefore, the switch between frequency regulation and time-shift arbitrage is frequent as shown in Fig. 9. The 1st and 2nd life segment switching times of the proposed planning coincide with the switching time of the planning in Case IV. But the proposed planning has better profitability than that of Case IV due to the multiple switches between the variable services after the 1st life segment.

It should be noted that frequency regulation is a more demanding service, which is embodied in the following two aspects:

1) Capacity requirements. With the degradation of battery capacity, in order to meet the AGC order in time, BESS has to purchase electricity from the power grid more frequently and be up against the risk of more power-shortage penalties, thus, the profitability of frequency regulation will be reduced. In this aspect, the proposed planning can continuously evaluate the profitability of frequency regulation and decide whether to switch to other services.

2) Market rules. The frequency regulation service markets in some countries or regions have restrictions on the access capability for BESS. Take the "Guangdong frequency regulation auxiliary service market trading rules" published in Sep. 2020 as an example, BESS will be prohibited from participating in the market if the energy capacity of BESS decays to 50% of the rated capacity (i.e. 1 MWh). Thus, in Case V, the BESS will be prohibited from being applied to frequency regulation again after participating in time-shift arbitrage. In this aspect, the proposed planning will apply BESS to other less demanding services after BESS participates in frequency regulation service for maximizing the benefits, which will be described in detail in the next section.

5.4 Planning universality evaluation to multiple market services

In the above analysis, the proposed planning is only applied to two available services in the whole life due to the easy comparison among different cases. For purpose of maximizing the overall benefit, BESS can flexibly participate in multiple available services under the electricity market rules throughout the whole life cycle, including peak shaving, delaying the upgrade of the distribution network, black start, and so on. In order to evaluate the universality of the proposed planning, the tested case of the proposed planning that we discuss in this section includes the services of peak shaving, frequency regulation, and time-shift arbitrage. Referring to the typical electric auxiliary service market trading rules, the j-th monthly discounted economic benefit of peak shaving $R^{j}_{\mathrm{REG.PV}}$ is specifically calculated as follows:

$$R^{j}_{\mathrm{REG.PV}}=\sum_{i=1}^{T_{\mathrm{MON}}}\left(E^{i}_{\mathrm{REG}}\times\rho^{i}_{\mathrm{REG}}-E^{i}_{\mathrm{BUY}}\times\rho^{i}_{\mathrm{BUY}}\right)(1+r/12)^{-m} \quad (40)$$

To simplify the analysis, take ρ^{i}_{REG} as 800 CNY/MWh. Referring to the actual charge/discharge strategy of one BESS station in operation, the charge period is set from 3:00 to 5:00 am and the discharge from 7:00 to 9:00 pm every day. The specific calculation of the case is implemented through the modified solution procedures in Section 4.3 based on Eq. (40). The obtained results are shown in Fig. 10 and Table 6.

From the results, we can find that the BESS is used for frequency regulation (**1st life segment**) firstly, is used for time-shift arbitrage (**2nd life segment**) later, and participated in peak shaving (**3rd life

segment) in the last few years. Although the service of peak shaving has the lowest benefits in the case, it still can contribute to maximizing the overall benefits of the multiple services. Obviously, the benefits NPV of three services is higher than that of the individual service and two services, which verifies the universality of the proposed planning to multiple market services. In addition, the proposed planning can be promoted to design the planning for more than three services effectively without upgrading the complexity of decision-making in planning.

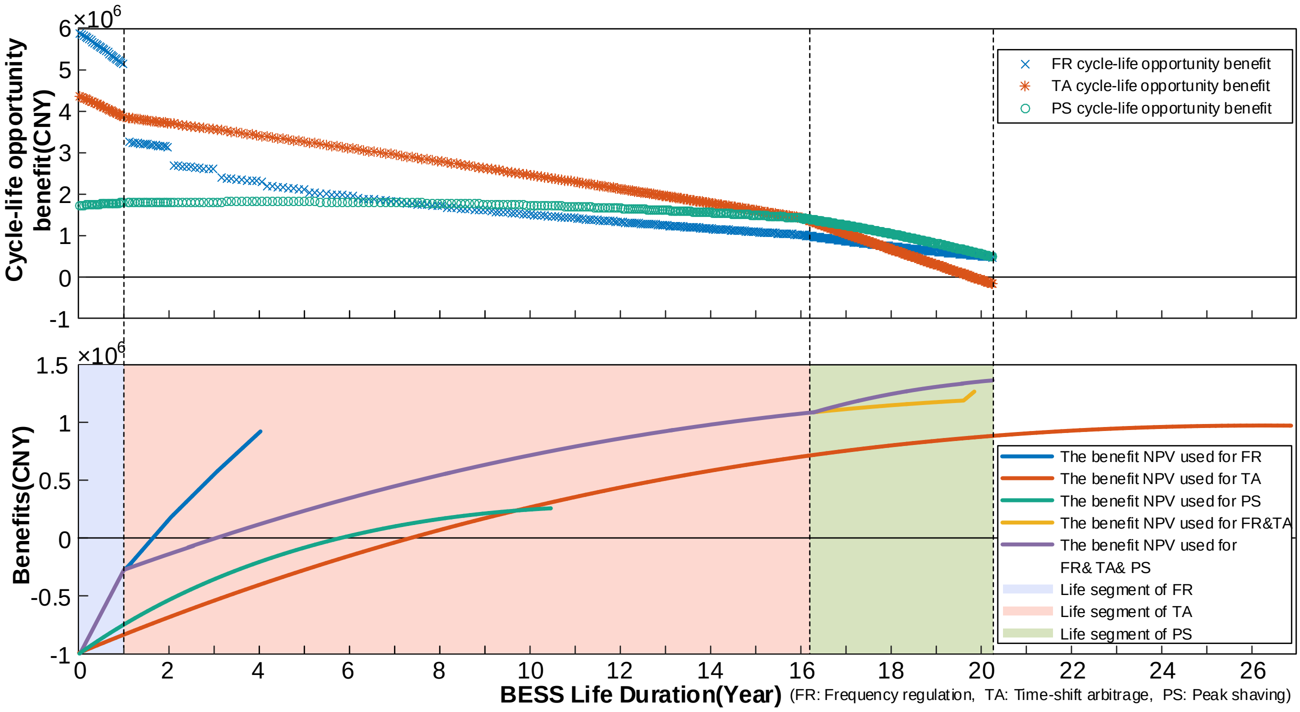

Fig. 10 The NPV of benefits used for the proposed planning including peak shaving

Table 6 Comparison of changes in NPV of benefits including/excluding peak shaving

The number of services	**Life segment**	**1st life segment**	**2nd life segment**	**3rd life segment**
2 (frequency regulation and time-shift arbitrage	**Duration (year)**	0~1.00	1.00~19.61	19.61~19.85
	Services	Frequency regulation	Time-shift arbitrage	Frequency regulation
	Accrued benefits NPV (CNY)	-285709.00	1209595.96	1277777.78
3 (frequency regulation, time-shift arbitrage, and peak shaving)	**Duration (year)**	0~1.00	1.00~16.17	16.17~20.25
	Services	Frequency regulation	Time-shift arbitrage	Peak shaving
	Accrued benefits NPV (CNY)	-285709.00	1066752.67	1368648.26

6. Conclusion and future work

This paper proposes optimal BESS planning to help the owners select the most profitable services dynamically in the whole-life cycle with normalized quantification of multi-services profitability by proposed cycle-life opportunity benefit, based on the improved battery life degradation model. The test results using existing market rules and actual operation data validate the economic superiority of the proposed planning. Compared with the individual, stacked, and successive services schemes, the overall benefits of the proposed method are increased by 39.9%, 34.8%, 138.5%, and 13.2%. Further case studies show that even higher revenue can be achieved when accounts for more than two services, which verifies the universality of the proposed planning to multiple market services without upgrading the complexity of decision-making. In addition, the application services can be accurately switched in response to the changes in actual market rules.

Future work can be conducted in the following directions: The data-based battery life model can be further developed to reflect the life degradation more accurately. Besides, the overall benefits model can be additionally improved by considering indirect benefits and environmental benefits.

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