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Construction Method of Ancillary Emergency Backup Service based on Battery Energy Storage System

1st YU Pengfei [a], 2nd ZHU Jizhong [b], 3rd JUN Liang [c], 4th CHEN Hongzhou [a], 5th XIONG Xiaofu [a]

[a] 1st School of Electrical Engineering, Chongqing University, Chongqing, China, E-mail address:ypf883@hotmail.com

[b] 2nd South China University of Technology, Guangdong, China

[c] 3rd Cardiff University School of Engineering, Cardiff, United Kingdom

Abstract—**The power systems with a high proportion of clean energy face both greater uncertainty in power generation and the threat of stability brought by low inertia. After a fault, the rapid drop in power grid frequency, large voltage fluctuations, and insufficient reactive power support can lead to new energy generation units being disconnected from the grid. Fast active and reactive support will play an important role in suppressing fault propagation in low-inertia systems and preventing large-scale power outages. The reserve and frequency regulation market is a necessary means to deal with power grid failure events, but many blackout events occurred due to insufficient reserve capacity and ineffective market transaction mechanisms. As a flexible power regulation resource, BESS (battery energy storage system) has been incorporated into the power ancillary service market planning. In some engineering cases, the frequency regulation ancillary service provided by energy storage has also shown its advantages. However, there is a lack of in-depth research on how to gather BESS to take part in AEBS (ancillary emergency backup services) in the early stage after the failure. Therefore, in view of the dynamic change of power system risks and the different response speed of different backup resources, this paper proposes to establish a segmented combined backup mode to realize the combination of emergency backup at the initial stage of failure and frequency regulation backup during the fault recovery process. A related model of AEBS demand assessment and emergency backup service pricing mechanism is established. And considering the capacity, life loss and opportunity costs of energy storage for AEBS, a LMP (locational marginal price) method is used to calculate the electricity price of AEBS provided by BESS. It has proved the effectiveness by constructing a grid AEBS based on BESS used by the IEEE 30 node system.**

Index Terms—**Battery energy storage system; Ancillary services market; Ancillary emergency backup services; Risk assessment; Locational marginal price**

I. INTRODUCTION

IN recent years, large-scale power outages such as the blackouts in India and in London are mainly because of the cascading failures in the grid [1-2]. Take the blackout in London on August 9, 2019 as an example, approximately 1.1 million customers lost power for a period between 15 and 45 minutes as a result of a series of events on the electricity system. These events caused significant disruption to many people in their homes and businesses, and some rail services in and around London being particularly badly affected along with wider cancellations and significant delays impacting thousands of passengers. Other critical facilities including Ipswich hospital (lost power due to the operation of their own protection systems) and Newcastle airport (disconnected by the Low Frequency Demand Disconnection scheme) were impacted as well [3].

In carbon neutrality goals, the high proportion of clean energy connected to the grid reduces the inertia of the power system. The impact of the fault will cause the system frequency to drop rapidly, requiring the power grid to increase the ability to control the source and load [4], and use the rapid response resources for emergency power support to achieve a balance between supply and demand [5-6].

In the future power systems, not only large-scale clean energy connect to transmission networks but also a large amount of distributed clean energy connect to distribution network. For instance, numerous hydropower, photovoltaic and wind power transmission in western China are usually more than 1,000 kilometers from the load centers in Eastern and Southern China. Therefore, the backbone network of the power systems will face multiple risks such as unstable network structure and unsecure power supply to loads. Under extreme natural disasters, power grids may not meet the N-1 criterion during the maintenance of electrical equipment, and large-scale power outages may occur from time to time. Usually, a power system will set a certain number of flexible reserves according to the fluctuation range of the loads, and set a certain scale of emergency backup according to the

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Corresponding author: YU Pengfei
E-mail address:ypf883@hotmail.com (YU Pengfei).

expected failure. The capacity reserve must be greater than the capacity of the largest unit in the system or a certain load ratio. In the face of large disturbances, if the fault cannot be cleared in time, conventional power systems usually rely on machine and load shedding to maintain the power grid safety. This deterministic principle suffices to deal with most unbalanced situations.

Response speed is the main factor for the standby performance of traditional standby units. The traditional units cannot respond quickly because of the limitation of the frequency modulation dead zone and the climbing speed, which makes it difficult to ensure the stable operation of the system [7]. The allocation of spares is optimal depending on the chosen aim, and the spare problem also can be well described using a deterministic model. However, the risk source in the future system has gradually shifted to the volatile renewable energy, which cannot be characterized by deterministic methods and models. It is because of the large deviation in the output forecast of renewable energy [8-9]. For a long time, system operators have been very conservative with regard to system risk issues, tending to prepare more reserves to minimize system risk levels. But the marginal cost of reducing risk is often incremental, which makes the system's alternate decision-making suboptimal. In fact, the resources provided for backup (such as hydropower, thermal power, BESS, etc.) not only have different response speeds, but also have different backup costs. The more refined the spare classification is adopted in the market, the better the division of different spare resources. Which can more motivate the reserve resources to participate in the reserve market in an orderly manner, and improve the system's ability to absorb renewable energy.

BESS (Battery energy storage system) has become effective means to improve the flexibility, economy and safety of the grid [10]. Thanks to advances in battery manufacturing technology, battery life and cost issues have been improved, making the demand for BESS technology in the market gradually increase. With the reform of energy structure, using large-scale BESS in the power grid is becoming more and more extensive [11]. The application scenarios of multi-aim energy management of hybrid energy and BESS are also becoming more and more common [12]. The goal of carbon neutrality also makes the application of BESS as a key part. The application of BESS has a positive effect on the supply side (smooth output fluctuations [13], improve frequency and voltage regulation capabilities, ect.), grid side (emergency power support, frequency regulation and power flow optimization [14-15]) and the demand side (power supply important loads [16]) of the power system. The excellent qualities of BESS at all levels in power systems can be distributed through the market. With the rapid development of the electricity market in recent years, the participation of BESS in the electric ancillary service market has attracted everyone's attention. Mature power markets such as PJM in the United States, the United Kingdom, and Australia have built ancillary service markets with energy storage participation. The peak shaving, frequency regulation and rotating backup services involved in energy storage are usually aimed at the small disturbance range of frequency and voltage during the static operation of the power grid.

Although the addition of BESS will greatly change and help the power systems, there are still some key issues worthy of study.

1）The choice of backup power location is related to the dynamic change of failure risk and is limited by network constraints. When the tie line is blocked or the key component fails, it cannot provide sufficient backup.

2）Insufficient reserve capacity or insufficient response speed cannot take into account various failure events, especially the high-risk events of multi-component failures in harsh weather environments.

3）In the reserve market, the cost difference of reserve resources is not considered, which is not conducive to stimulating the development for fast and flexible response reserve resources such as BESS.

Further, the above-discussed problem will be considered as basic problem in this research. To solve the above-mentioned issues, it is requisite collaboration with multiple research sites. The dynamic risk early warning method makes the spare capacity of reserve nodes more accurate.

In smart grids, risks are positively correlated with the occurrence of failures, and an increase in system risks means a more volatile system with a higher probability of failures. The concept of dynamic risk assessment of power grid can make up for some of the main problems of current risk assessment [17]. According to the analysis of the fault influence range, the state duration sampling method, the entropy weight method, the risk scenario screening and other risk assessment methods, an overall design scheme of the urban power grid operation risk assessment system is proposed. A dynamic risk mitigation strategy based on dynamic state estimation was proposed to eliminate the threat of unknown inputs to the power grid and potential cyber attacks [18]. A new real-time risk assessment model method was proposed for thunderstorms [19]. These previous works mainly payed attention to the correlation between system risk and system security, either improve the method itself, or focus on risk to assess grid reliability and resilience. This paper does not focus on these discussions, but only uses the latest real-time risk methods applied in emergency markets to solve the above problems 1 and 2.

The excellent quick response speed of BESS has attracted widespread attention as emergence reserve resources. The emergence of millions of megawatt-level BESS has played an important role in large-scale integration of clean energy sources as well as safe and stable operation of the power grid. With the establishment of the communication channel, it can reduce the response time of the energy storage system to less than 100ms. Regarding the emergency power support of energy storage taking part in the grid, the literature [9] applies the energy storage system and demand response scheme to the microgrid, and finds the support power demand based on the day-ahead market and real-time market, which improves the economics of microgrid operation.

Reserve sizing approaches can also be categorized into static and dynamic methods. Static methods typically pre-determine reserve requirements for long time periods (e.g., one year), while dynamic methods assess it for more frequent periods, depending on the current or expected status of the system. While in [20], [21], [22], static reserve sizing methods have been investigated, in [23], [24], [25], [26] dynamic methods have been proposed. As short-term variations in the generated power by RES and the electricity demand from gate closure through to real-time result in dynamic balancing requirements, to ensure grid reliability, a dynamic reserve sizing model is more appropriate. However, previous works on dynamic reserve sizing either use parametric approaches like [23], [24], [25], which do not consider the true distributions of forecasting errors, or they use non-parametric approaches [26] in combination with convolution theory to calculate the error distribution associated with the system. Much of the work has focused on methods to develop better probabilistic forecasts, and only recently has it moved to applications. Traditionally, reserve requirements are determined by rules-of-thumb (static reserve requirements, e.g., NERC Reliability Standards), and more recently, dynamic reserve requirements from tools and methods which are in the adoption process such as Dynamic Assessment and Determination of Operating Reserve (DynADOR), Dynamic Reserves Dimensioning (DRD), and RESERVE. To date, utilities and ISOs do not explicitly utilize probabilistic forecasts in the scheduling and dispatch stages. To bridge this gap, this work focus on to combine the node dynamic operating reserve determination with the ancillary emergency market after a fault. This work can illustrate the feasibility of BESS reverse to deal with dynamic risks in real ancillary market.

The general definition of market services in which BESS participates is quite clear, but different regulators around the world are not always consistent in the specific services they provide. A classification inspired from the North American ancillary services distinguishes four types of services: regulation, spinning reserve, non-spinning reserve and replacement reserve while in Europe only three different services can be distinguished: primary, secondary and tertiary.

There are many literatures analyzing BESS participation in the market from the perspective of game theory [27,28,29,30]. But from the market designer's point of view, the mechanism also needs to be carefully designed to accommodate BESS participation. There are generally two mechanisms for BESS market participation. The first mode is to establish an independently operated market for storage usage rights, where generators or consumers can purchase usage rights from storage owners by centralized auction [31], collective sharing [32], bilateral contracting [33] or peer-to-peer trading [34]. This mode operates easily, but cannot guarantee the optimal allocation of the storage resources. The second model is to integrate BESS into the existing electricity market, and the settlement model will jointly dispatch all resources and determine the settlement result that maximizes benefits. This model can theoretically reach the global optimum, so it is accepted by the North American market. In February 2018, Federal Energy Regulatory Commission (FERC) issued Order 841 [35], requiring the independent system operators (ISO) to facilitate direct market participation of the ESSs.

PJM defines a new resource model named Electric Storage Resource (ESR) [36]. Under this model, the ESSs can submit their cost curves for energy provision and utility functions for energy consumption. Based on the collected parameters, PJM will clear the market, determine the scheduling plans and generate locational marginal prices (LMP) [37-38]. The new model takes a big step forward, but the energy exchanged with the market are settled at the time-variant LMP, this might distort their incentives to behave honestly [39-40]. To address this shortcoming, this paper introduces a punishment mechanism to curb the occurrence of such dishonest behavior which also solve the above problem 3.

In view of the above problems, this paper proposes a dynamic meteorological risk prediction method to quantify the node-based risk level and obtain the current node's reserve capacity demand during the high-risk time period of the power grid in the severe weather process. In this paper, rapid response resources such as energy storage are incentivized to participate in the subdivided ancillary emergency backup service (AEBS) market, and the introduction of a penalty mechanism curbs dishonest competition in node pricing methods. As a result, the precise AEBS of the power system is realized, which greatly reduces the security risk of the power grid and reduces the backup cost. The contributions of this paper are summarized as follows.

1, This paper proposes an emergency service market in which BESS can compete reasonably, fully considering the SOC of energy storage equipment, which is different from the existing traditional ancillary service market.
2, This paper introduces dynamic risk into the AEBS market, which can more accurately and proactively determine the dynamic demand and transaction pricing of BESS on risk nodes.
3, This paper introduces a penalty mechanism to curb the occurrence of dishonest behavior in the LMP method.

The rest of paper is organized as follows. Section II presents the typical application scenarios of emergency backup service of power system. Section III explains how risk forecasting participates in ancillary market processes. Section IV and V describes each step of the proposed methodology. A case study is reported in section VI, while conclusions are drawn in the last section.

II. TYPICAL APPLICATION SCENARIOS OF EMERGENCY BACKUP SERVICE OF POWER SYSTEM

When a power system experiences a fault, the faulty components will be removed due to the protection action, resulting in power imbalance or voltage and frequency fluctuations. The emergency backup of the power system enables power regulation to compensate for this unbalanced power or to regulate voltage and frequency.

A. Emergency power support needs

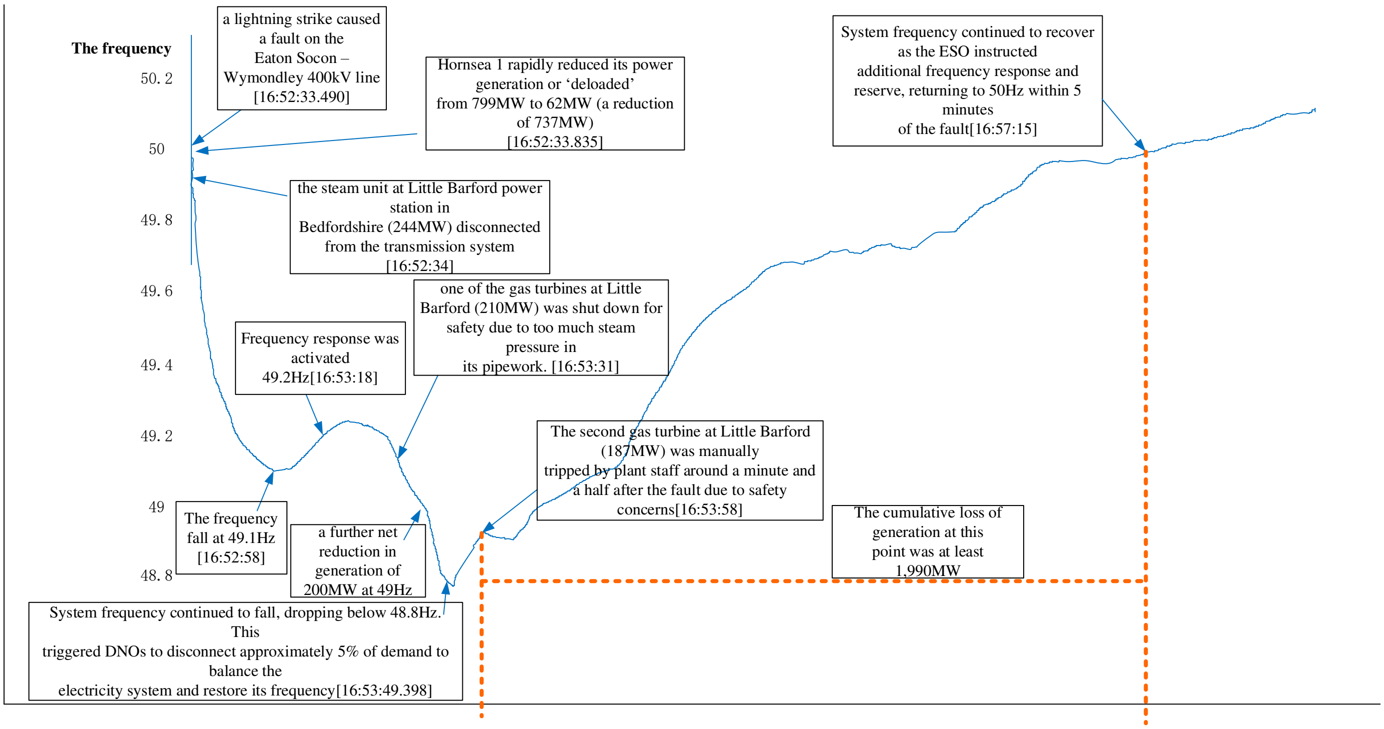


Fig. 1 Time series and frequency variations of accidents [3]

When a fault occurs, if the adjustment is not timely enough, a cascading failure will occur, resulting in a series of losses. That is why the emergency power support is needed. Fig. 1 is the frequency change process during the "8.9" blackout in the UK in 2021. After the system is disturbed, the frequency drop has a developmental process due to the inertia of the unit. In the process of frequency reduction, the unit and other ancillary frequency modulation methods are continuously added to play a regulating role to prevent frequency reduction. Due to the relay protection action after the first fault occurs, the frequency modulation resources cannot immediately put into use. Other cascading outage events may occur before frequency regulation resources are activated. It can be seen from the incident of 8.9 that when the frequency regulation resources determined by the expected accident are not enough to balance the power shortage of the system, it ultimately uses load shedding means to maintain the frequency stability.

$$\mathrm{ROCOF}=\frac{f_0}{2\mathrm{H}_{\mathrm{sys}}}\frac{\Delta P}{\mathrm{S}_{\mathrm{base}}}=\frac{f_0\Delta P}{2\mathrm{E}} \qquad (1)$$

Where, ROCOF is the frequency change rate, $\mathrm{H}_{\mathrm{sys}}$ is the inertia of the system, $\mathrm{S}_{\mathrm{base}}$ is the reference capacity of the system, E is the inertial energy of the system, and ΔP is the power change. Obviously, in the dynamic process, the quicker the support function of the backup adjustment resources invest, the smaller power change(ΔP) will get. Which will lead a smaller frequency change rate, the system frequency drops slower. Therefore, the longer the time window left for system adjustment resources to participate in adjustment, and cascading events are less likely to occur.

B. Cascading events suppression requirements

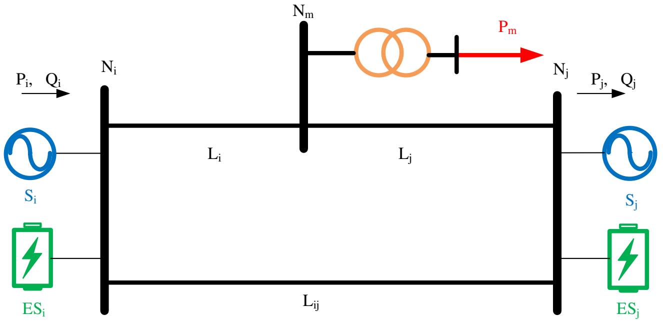


Fig. 2 Typical power system structure diagram with energy storages

Take the power system shown in Fig 2 as an example, what if set BESS ES_i and ES_j (integration of multiple energy storage devices) at the sending-end system S_i and the receiving-end system S_j , and the system S_i connect the system S_j through the line L_i, L_j and L_{ij}. When a failure happens, start the energy storage device ES_i at the sending end to absorb excess power or start the energy storage device ES_j at the receiving end to discharge the power.

The above scenarios show that the BESS backup can be used not only for frequency stabilization, but also for safety control such as cascading suppression after a grid failure. Therefore, alternate start conditions need to be diversified. Under different risk conditions, it is not appropriate to simply determine the reserve capacity according to the capacity of a generator set.

III. EMERGENCY BACKUP SERVICE MODE BASED ON BATTERY ENERGY STORAGE

A. Reducing energy storage emergency backup service capacity based on dynamic risk assessment

In order to reduce the unnecessary spare capacity and reduce the costs of spare service, it is the key factor to construct a low-cost spare system to evaluate the dynamic risk and propose a more accurate spare demand. Dynamic risk assessment is an effective means to determine the size of the spare. According to the time scale of dynamic risk assessment, it is possible to purchase the determined emergency reserve scale needed for the next day in the day-ahead market. It is also possible to conduct ultra-short-term risk assessments within the day to determine subsequent short-term backup needs.

B. BESS's participation in process of emergency backup services transaction in day-ahead markets

In a day-ahead market, the emergency backup service and spot electric energy transaction clearing mode are adopted in sequence. Because the post-fault control strategy based on the results of short-term fault prediction, the first step is to evaluate the operation risk of the power grid on the next day. The unit combination in the traditional unit power market comes next. The second step is to complete the pre-economic dispatch before the day, including the pre-clearance of determine the bid-winning capacity, service type (charging, discharging, voltage support), service time interval and emergency backup of each energy storage power station service fee both in the spot electric energy and emergency backup service market.

The transaction mode of the emergency backup service market in the day-ahead market is shown in Figure 3. Each energy storage power station determines whether to quote and bid according to the operating cost of the power station, the forecast of the electricity market demand for the next day and its own optimal operation decision-making situation.

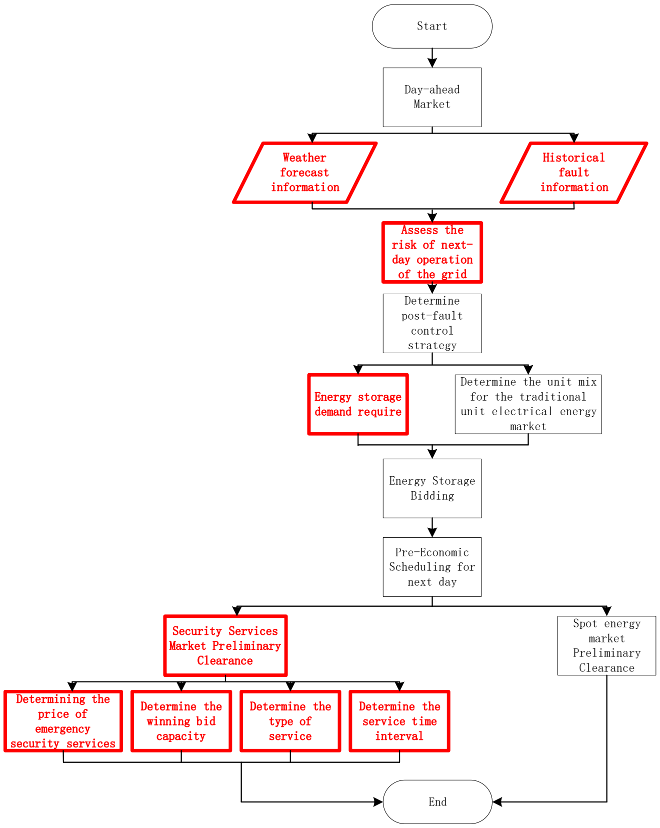


Fig. 3 Emergency backup service market transaction model in the day-ahead market

C. BESS's participation in process of emergency backup services transaction in the real-time market

The shorter the early warning period of failure risk, the more accurate the prediction. Therefore, the emergency backup service can better reflect advantage in the real-time market. As shown in Figure 4, the real-time market can dynamically publish the emergency backup service start time, emergency backup service type, emergency backup service capacity, and emergency backup service duration according to the failure risk early warning result. The release cycle can be set to 10~15min. Each energy storage power station quotes and bids according to its operating cost of the power station and real-time SOC.

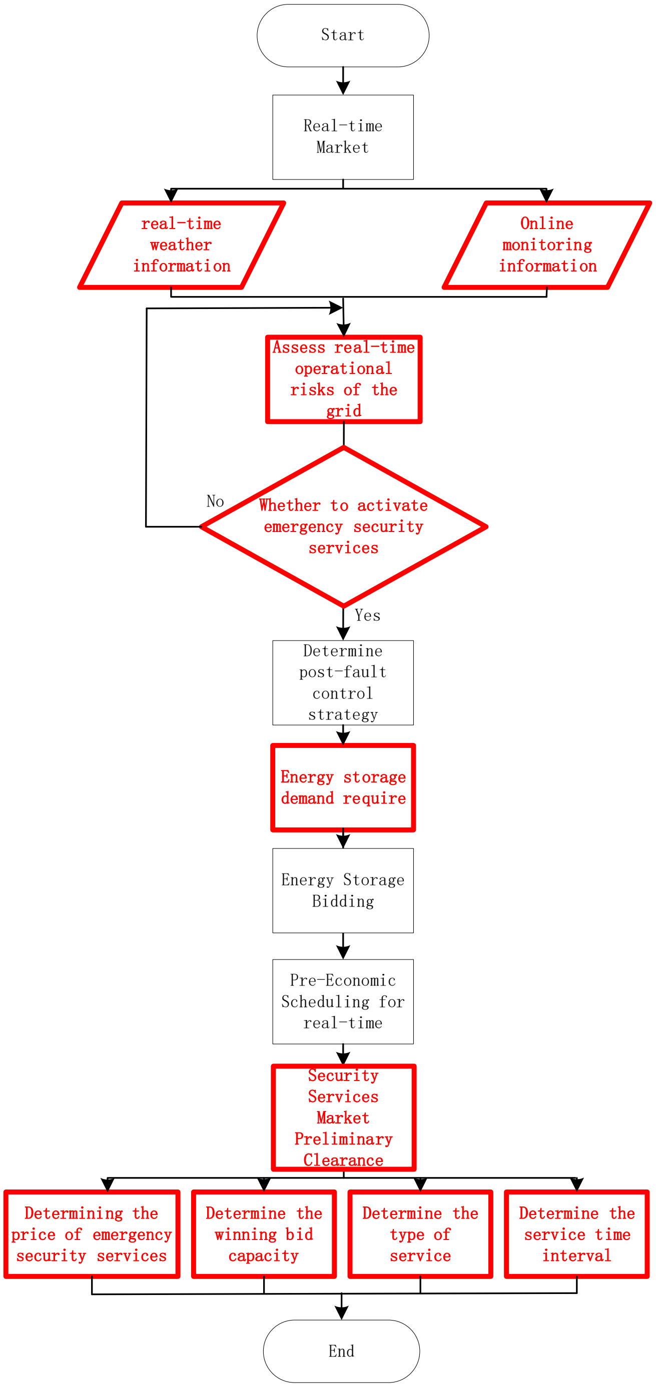


Fig. 4 Emergency backup service transactions in the real-time market

IV. ESTIMATION OF EMERGENCY BACKUP SERVICE NEEDS BASED ON REAL-TIME RISK ASSESSMENT

When accumulating adjustable resources such as BESS to take part in the AEBS of the power system, it is necessary to estimate the emergency support power, capacity and duration time required to maintain system security according to the risks faced by the grid operation, and publish them on the ancillary service market.

A. *Real-time Risk Assessment*

There have been many studies on power system operation risk assessment [36]. Because of the complex operating environment, transmission lines have a high probability of failure under severe weather. This paper takes the transmission line as an example to analyze the risk caused by its outage, and it can also use the method for the risk analysis of plant and station equipment.

1) Line failure rate prediction

In the statistical method of long-term average failure rate of transmission lines, they approximate that the line failure frequency is equal to the average failure rate of the line. Considering the influence of severe weather, we calculated the average failure rate of the line according to the line failure ratio coefficient under different meteorological factors. If the number of failures of the line in the period T_{f} of the f-type meteorological disaster (thunder and lightning, typhoon, strong wind, ice and snow, high temperature, heavy rain, wildfire, etc.) is n_{f}, then the failure rate and failure probability of the transmission line are expressed as:

$$\lambda_{\mathrm{f}} = \frac{n_{\mathrm{f}}}{T_{\mathrm{f}}} \tag{2}$$

$$P_{\mathrm{f}} = \frac{\lambda_{\mathrm{f}}}{\lambda_{\mathrm{f}} + \mu_{\mathrm{f}}} \tag{3}$$

Where: λ_{f}, μ_{f} and P_{f} are respectively the line failure rate, line repair rate and failure probability under category f meteorological disasters.

Accepting tropical storm for instance, when the hurricane goes through the power framework, the line m's failure rate is connected with the line length, geographical variables, and storm way distance [17]. In order to calculate the real-time failure rate of the line, we divide the transmission line into n unit blocks and then use Equation (4) to calculate the probability of each unit block operating reliably:

$$\mathrm{P}_{\mathrm{n}} = 1 - k_1 \mathrm{e}^{-k_2 x_n} \tag{4}$$

In the formula: k_1 and k_2 are the balance coefficient and the typhoon influence coefficient (got from historical statistical data); x_n is the distance between the unit block and the typhoon path.

Then the failure rate of the mth transmission line is as follows.

$$\mathrm{P}_{\mathrm{m}} = 1 - \prod_{\mathrm{n}} P_n \tag{5}$$

This failure rate can determine whether to activate the emergency backup service.

When $\mathrm{P}_{\mathrm{m}} > \mathrm{P}_{\mathrm{zd}}$ (set the threshold for starting the service), it can start the market publishing process.

2) Risk duration index

In order to predict the risk of the line at different time scales, Risk time index using transmission line outage duration and failure time interval under predicted meteorological disasters.

$$\mathrm{TTR}_{\mathrm{kif}} = \mathrm{tr}_{\mathrm{ki}} - \mathrm{tf}_{\mathrm{ki}} \tag{6}$$

$$\mathrm{MTTR}_{\mathrm{i}} = \frac{\sum_{\mathrm{k}} \sum_{\mathrm{i}} \mathrm{TTR}_{\mathrm{kif}}}{\mathrm{n}_{\mathrm{f}}} \tag{7}$$

$$\mathrm{TBF}_{\mathrm{ki}} = \mathrm{tf}_{\mathrm{ki}} - \mathrm{tf}_{\mathrm{ki-1}} \tag{8}$$

$$\mathrm{MTBF}_{\mathrm{k}} = \frac{1}{\mathrm{n-1}} \sum_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{TBF}_{\mathrm{ki}} \tag{9}$$

Where: *n* is the number of failures, *T* is the duration of natural disasters, $\mathrm{TTR}_{\mathrm{kif}}$ is the outage time of the *i*th failure of the *k*th transmission line; $\mathrm{TBF}_{\mathrm{ki}}$ is the time interval between two failures of the *k*th line, $\mathrm{tr}_{\mathrm{ki}}$ is the recovery time after the *i*th trip of the *k*th line, $\mathrm{tf}_{\mathrm{ki}}$ is the *i*th trip time of the *k*th line; $\mathrm{tf}_{\mathrm{ki-1}}$ is the *i*-1th trip time of the *k*th line; $\mathrm{MTBF}_{\mathrm{k}}$ is the meantime interval between failures of the *k*th line; *n* represents the total number of failures of the *k*th line.

3) Power shortage index

After obtaining the line failure rate, the state sampling method is used to analyze the system status and calculate the system risk indicators. Based on the refined time scale, this paper uses the expected value of insufficient electricity in the power system risk assessment to characterize the grid risk.

$$\Delta \mathrm{EENS}(\mathrm{t}) = \sum_{s\in \mathrm{F}} \frac{m(s)}{\mathrm{M}} \times \mathrm{C}(s) \times \mathrm{t} \qquad (10)$$

Where: $\Delta\mathrm{EENS}(\mathrm{t})$ is the expected value of insufficient power; $m(s)$ is the number of times the system state s appears in the sampling; F is the system failure state set; M is the total number of system state samples; $\mathrm{C}(s)$ represents the load shedding of the system state s; t is a time interval, which takes the outage time of Equation (5), i.e. $\mathrm{t}=\mathrm{TTR}_{\mathrm{kif}}$.

V. BESS-BASED MARKET PRICING FOR AEBS

In the ancillary service market, it is necessary to analyze related issues such as cost, price and settlement to establish a special transaction mechanism for emergency backup service needs. The following is an analysis of BESS participation in the emergency services market.

A. Objective function

In order to establish a clearing model for BESS to provide emergency power support, we must clarify the use cost of energy storage first.

1) Energy storage cost

The operating cost of BESS taking part in AEBS includes investment cost $\mathrm{C}^{\mathrm{cap}}$, mileage cost C^{mil} and opportunity cost C^{opp} . Particularly, the capacity cost is the BESS capacity investment cost decomposed to each control cycle, and the mileage cost C^{mil} is the sum of capacity cost C^{energy} and the life loss cost C^{loss}. The specific calculation method of each cost is:

a）Investment cost sharing

$$\mathrm{C}^{\mathrm{cap}} = \sum_{t\in T}\sum_{i\in I} \frac{r(1+r)^{T_{\mathrm{shelf}}}}{(1+r)^{T_{\mathrm{shelf}}}-1} \frac{c_i E_i \Delta t}{\mathrm{YD}} \qquad (11)$$

In the formula: E_i is the total investment capacity of BESS, r is the discount rate, T_{shelf} is the fixed life of BESS (independent of the charging and discharging behavior of BESS), Y, D, and Δt are respectively year, day and unit time,

b）mileage cost

Loss of life cost C^{loss}

Factors mainly affected the life loss of BESS, such as depth of discharge (DOD), discharge rate, charge rate limitation, and ambient temperature. In order to simplify the life loss modeling, we assumed the BESS has an air temperature control system (i.e., a constant ambient temperature) and a fixed upper and lower charge and discharge limit. With the same depth of discharge, different energy storage states of charge will lead to different life losses. Taking to be true that the state of charge of the BESS for storing is experienced, the depth of discharge is the difference between the state of charge at the start and the end of the BESS for storing discharge, namely.

$$\mathrm{DCR}_{\mathrm{t}} = \frac{SOC_{t-1} - SOC_t}{\Delta \mathrm{T}} = \Delta \mathrm{SOC}_{\mathrm{t}} \qquad (12)$$

In the formula: SOC_t and SOC_{t-1} are the state of charge of energy storage at time t and the previous time t-1respectively; $\mathrm{DCR}_{\mathrm{t}}$ is the discharge rate of energy storage; $\Delta\mathrm{T}$ is the unit time.

Appendix A1 Figure A1 shows the relationship between the depth of discharge and battery cycle life for lithium batteries [18] which can be expressed by the following formula:

$$\mathrm{f(D)} = \mathrm{N}_0 D^{-\omega} \qquad (13)$$

In the formula: N_0 is the equivalent number of cycles for the energy storage charge-discharge at 100% depth, ω is a constant describing the relationship between the number of cycles and the depth of discharge set to 1.1~2.2.

Considering the impact of the state of charge during the operation cycle, the life loss cost of energy storage [19] is:

$$C^{\mathrm{loss}} = \frac{c}{E\beta^2 N_0}((1-SOC_t)^{\omega} - (1-SOC_{t-1})^{\omega}) \qquad (14)$$

In the formula: c is the capacity investment cost of energy storage, E is the capacity of energy storage, and β is the discharge efficiency of energy storage.

The multiple linear regression method linearizes the above formula [14] into the following formula:

$$C^{\mathrm{loss}} = \mathrm{a}SOC_t + \mathrm{b}SOC_{t-1} + \mathrm{c}DCR_t + \mathrm{d} \qquad (15)$$

In the formula: a, b, c, d are all coefficients.

energy cost C^{energy}

$$C^{\text{energy}}=\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{\text{energy}}P_{i,t}^{\text{cap}}(\frac{1}{\beta_i^{\text{dis}}}-1)\Delta t \qquad (16)$$

Δt is unit time, $\lambda_{i,t}^{\text{energy}}$ is the reference price for clearing the electric energy market, $P_{i,t}^{\text{cap}}$ is the bidding power for the safety service of the energy storage power station *i* in the time t, and β_i^{dis} is the discharge efficiency of the energy storage.

Thus, the mileage cost is:

$$C^{\text{mil}}=C^{\text{loss}}+C^{\text{energy}} \qquad (17)$$

c) opportunity cost

After it used BESS as an AEBS, it must consider the loss caused by its inability to take part in the electric energy market or ancillary service market because of the provision of AEBS. Referring to the analysis in Section 2, the opportunity cost of energy storage as a backup only considers the loss of revenue caused by the occupation of its electricity space, and does not consider the time cost during the backup maintenance period.

Theoretically, the opportunity cost of BESS should be the maximum benefit in the electric energy market or the ancillary service market. Compared with the electric energy market, although the market unit price of ancillary services is higher, considering the uncertainty of the ancillary services market, its benefits are not stable.

Therefore, this paper chooses the total revenue of the electric energy market as its opportunity cost, and its calculation method is the difference between the electric energy market revenue before and after deducting the declared capacity of the AEBS, the opportunity cost of the BESS to take part in the AEBS market [19] as follows Mode:

$$C^{\text{opp}}=C^{\text{EB}}-C^{\text{ER}} \qquad (18)$$

$$C^{\text{EB}}=\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{\text{energy,b}}P_{i,t}^{\text{cap,b}}\Delta t \qquad (19)$$

$$C^{\text{ER}}=\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{\text{energy,r}}P_{i,t}^{\text{cap,r}}\Delta t \qquad (20)$$

Where: C^{EB}, $\lambda_{i,t}^{\text{energy,b}}$, $P_{i,t}^{\text{cap,b}}$ are the revenue, unit price and power of energy storage taking part in the electric energy market before deducting the security service declared capacity. Correspondingly, C^{ER}, $\lambda_{i,t}^{\text{energy,r}}$, $P_{i,t}^{\text{cap,r}}$ is the income, unit price and power of energy storage taking part in the electric energy market after deducting the capacity declared for security services. Since the AEBS market is cleared before the electric energy market, to improve on the computation, this article accepts that the price of the electric energy market previously ($P_{i,t}^{\text{cap,b}}$) and later ($P_{i,t}^{\text{cap,r}}$) is equivalent.

In light of explaining the expense of every BESS stockpiling partaking in the AEBS market, all members should limit the total cost of participating in the ABES, in particular:

$$\min C=\mathrm{C}^{\text{cap}}+C^{\text{mil}}+C^{\text{opp}} \qquad (21)$$

This problem is essentially a scheduling problem, and the price of electricity is the result got by the dual problem of this problem.

B. Restrictions

1) Security constraints

The total capacity of energy storage bidding should be greater than the expected value of insufficient electricity:

$$\sum_{i\in I}P_{i,t}^{\text{perf}}\Delta t\geq \mathrm{EENS_i},[\lambda_t^{p}] \qquad (22)$$

In the formula, the $P_{i,t}^{\text{perf}}$ variable connected with the working expense of AEBS is the bid capacity of the AEBS of the BESS i in the period t.

2) Charge constraint

$$SOC_{i,t}+\frac{P_{i,t}^{\text{cap}}\Delta t}{\beta_{\text{dis}}}=SOC_{i,t-1},[\mu_t^{\text{ps}}] \qquad (23)$$

3) Energy storage operation constraints

$$\mathrm{SOC}_i^{\min}\leq SOC_{i,t}\leq \mathrm{SOC}_i^{\max},[\gamma_{i,t}^{\max},\ \gamma_{i,t}^{\min}] \qquad (24)$$

$$\mathrm{P}_{i,t}^{\mathrm{cap,min}} \le P_{i,t}^{\mathrm{cap}} \le \mathrm{P}_{i,t}^{\mathrm{cap,max}}, \left[\eta_{i,t}^{\max},\ \eta_{i,t}^{\min}\right] \qquad (25)$$

In formulas (22)- (28), $\mathrm{SOC}_i^{\min}$ and $\mathrm{SOC}_i^{\max}$ are the corresponding minimum and maximum capacities of the energy storage power station, respectively, $\mathrm{P}_{i,t}^{\mathrm{cap,min}}$ and $\mathrm{P}_{i,t}^{\mathrm{cap,max}}$ are the minimum and maximum operation of the energy storage power station, respectively Power, λ_t^p、μ_t^{ps}、$\gamma_{i,t}^{\max}$、$\gamma_{i,t}^{\min}$、$\eta_{i,t}^{\max}$、$\eta_{i,t}^{\min}$ are the Lagrangian multipliers corresponding to each formula.

4) Line Safety Constraints

$$\max\left\{p_{jk}(t); p_{kj}(t)\right\} \le \mathrm{P}_{jk}^{\max} \qquad (26)$$

where $p_{jk}(t)$ is the power flow from node *j* to node *k* on line *jk* at time t, and $\mathrm{P}_{jk}^{\max}$ is the maximum current carrying capacity on line *ij*.

C. Emergency backup service price setting

In this paper, the LMP method is used to calculate the electricity price for energy storage participation in security services, which is conducive to absorbing a high proportion of renewable energy. It showed the Langrangian function corresponding to the model in Appendix A, Equation A1. The Lagrangian function L is got by summing the dual multipliers of the aim function and constraints in the energy storage emergency power model, including the capacity cost $\mathrm{C}^{\mathrm{cap}}$, mileage cost C^{mil} and opportunity cost C^{opp} of energy storage, safety constraints, charge constraints, energy storage The dual multipliers, λ_t^p, μ_t^{ps}, $\gamma_{i,t}^{\max}$, $\gamma_{i,t}^{\min}$, $\eta_{i,t}^{\max}$, $\eta_{i,t}^{\min}$ corresponding to the running constraints.

For this model, to satisfy the declared capacity of each energy storage power station $P_{i,t}^{\mathrm{perf}}$ corresponding to the power shortage as the optimization aim, the partial derivative of the Lagrangian function L is equal to 0. According to the definition of LMP, the partial derivation of the optimal target power generation cost function to power is defined as the node electricity price at the access point of the energy storage device, then the electricity price derivation process of each BESS taking part in the AEBS is as shown in Equation (27), and the finally price is shown in formula (28).

$$\begin{aligned}\frac{\partial L}{\partial P_{i,t}^{\mathrm{perf}}} &= \lambda_{i,t}^{\mathrm{energy}}\frac{1}{\beta_i}\Delta t - \lambda_t^p \Delta t - \mu_t^{\mathrm{ps}}\Delta t\frac{\Delta t}{\beta_i} \\ &\quad + \eta_{i,t}^{\min}\Delta t - \eta_{i,t}^{\max}\Delta t = 0\end{aligned} \qquad (27)$$

$$\begin{aligned}\lambda_{i,t}^p &= \frac{\partial L}{\Delta t \partial P_{i,t}^{\mathrm{perf}}} \\ &= \lambda_{i,t}^{\mathrm{energy}}\frac{1}{\beta_i} - \mu_t^{\mathrm{ps}}\frac{\Delta t}{\beta_i}\end{aligned} \qquad (28)$$

In the above formula, $\lambda_{i,t}^p$ is the marginal quotation of the *i*th energy storage power station. We can see that it related the electricity price to the market clearing price of electric energy, the discharge efficiency of the energy storage power station, and the state of charge.

It is noteworthy that the constraint (23) can be appropriately relaxed after each BESS reaches the specified minimum capacity. The purpose of AEBS is urgency, and the continuous power supply to support critical loads is a priority. This article assumes that the declared electricity price of the BESS with the lower limit of the adjusted capacity is:

$$\lambda_{i,t}^{\mathrm{after}} = k_3 \lambda_{i,t} \qquad (29)$$

Where k_3 is the balance coefficient.

D. Emergency backup service market settlement method

1) BESS's normally participation in AEBS

The AEBS control center gives a request for BESS operator participants to take an interest in crisis control, in view of the risk evaluation results. Whenever the emergency happens, the BESS operators who have marked an agreement with the safety control center and can play out the agreement typically, can get the benefits of AEBS for each time span.

$$F_{i,t} = \lambda_{i,t}^{\mathrm{q}} P_{i,t}^{\mathrm{q}} \Delta t \qquad (30)$$

Where the final clearing price and clearing capacity of each energy storage are represented by $\lambda_{i,t}^{\mathrm{q}}$ and $P_{i,t}^{\mathrm{q}}$, respectively.

The profit of the emergency backup service of energy storage taking part in each time period is:

$$p_i=\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{\text{after}}P_{i,t}^{\text{cap,r}}\Delta t\text{-}C \qquad (31)$$

2) BESS's dishonesty punishment in emergency backup services

When energy storage fails to provide AEBS, it is subject to temporary financial penalties. The penalty fee for the BESS that fails AEBS in each period is:

$$F'_{i,t}=\alpha\lambda_{i',t}^{\text{q}}P_{i,t}^{\text{q}}\Delta t \qquad (32)$$

In the formula, $F'_{i,t}$ is financial penalties for energy storage operators who fails to provide emergency backup services, α is the declaration penalty coefficient of the emergency reserve service market, $\lambda_{i',t}^{\text{q}}$ is the electricity price for the emergency standby service control center to purchase emergency standby services from additional energy storage operators, $P_{i,t}^{\text{q}}$ is the capacity cleared by the original energy storage operator.

Through the above strategies, the checking and early admonition of various dangers during the activity of the framework can be understood, and the power lack brought about by high-risk occasions can be expected and delivered in the AEBS market. Risk type and intensity are related to the final AEBS demand, while the available BESS service resources and power shortage needs of the system framework link the service pricing.

In the event of a grid emergency, power shortages may happen at several nodes in the grid, especially when multiple elements, like N-2 or N-3, are out of service. In such situation, the optimal solution is to implement on-site BESS support at each node to balance the power shortage and avoid the exchange of power flow on the unstable power grid. Hence, it is advised to purchase electricity from the region's market according to each node's individual demands. If there is no or very little energy storage capacity for one node's area, it should be purchased from a larger or other power market.

VI. CASE ANALYSIS

This paper prioritized the local purchase of energy storage emergency backup according to the power shortage of a single node. The case study takes node 5 as the observation node and considers the situation that the node contains five different types of energy storage, so as to reflect the difference in the initial state of charge and cost of different types of energy storage. Accordingly, the power shortage of each node and various types of energy storage capacity compensated locally can be calculated according to the processing method of node 5.

The IEEE30 node system after adding energy storage power stations was used to verify the proposed model of BESS taking part in the AEBS market. The energy storage devices BESS1~BESS5 are all connected to the Bus5 node. The types include lithium batteries, sodium-sulfur batteries, and lead-acid batteries. Table 1 shows the parameters of these devices. And the life loss coefficient a=-36.23, b= 34.80, c=2.77, d=-2.45, k_3=1.1:

TABLE 1
ENERGY STORAGE POWER STATION PARAMETERS

Available energy storage power station at Bus5 node	Capacity /MW·h	Initial SOC /MW·h	Power /MW	Charge-discharge conversion efficiency /%	Cost /10^4Yuan
BESS1	20	16	20	95	7500
BESS2	20	15	15	80	6000
BESS3	10	7	10	85	4800
BESS4	10	6	5	95	3000
BESS5	5	3.5	5	90	2000

The transaction clears at the marginal price. Each AEBS provider submits the supported energy storage power, duration (greater than or equal to 10min), and price to the trading center. The trading center ranks the suppliers' prices from low to high. When the demand for emergency service is in balance with the cumulative support power of the M$^{\text{th}}$ and previous suppliers, the M$^{\text{th}}$ supplier's quotation is used as the marginal electricity price for AEBS, which is also the settlement price of all M BESS service providers.

Each service is settled separately, paid monthly, and completed simultaneously with the electricity bill of the current month. And the settlement method is the same as the electricity bill. There can be multiple service incomes in a month.

A. *Power shortage*

1) Line failure rate calculation

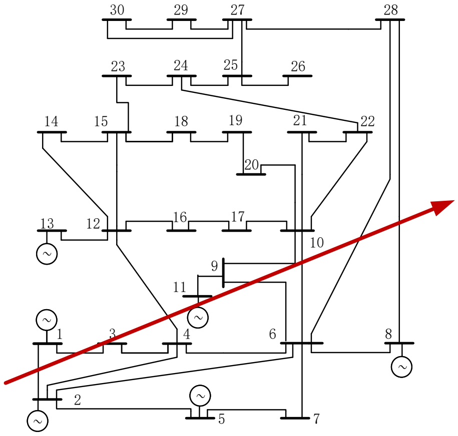


Fig. 5. Diagram of typhoon path

Figure 5 shows the path the typhoon that lasts in 4 hours. Take k_1=0.15 and k_2=0.23[37]. According to equations (2) and (3), calculate the failure rate of each transmission line at each time of the system framework. The failure rate of each transmission line in the last cycle shows in Appendix A Table A1:

2) Power support demand forecast

It showed the average outage time of 500kV lines in a certain province under different meteorological factors in Table 3 [20]. In this paper, we selected the average outage time under the action of typhoon as the basis for demand calculation.

TABLE 2
MTTR UNDER DIFFERENT METEOROLOGICAL FACTORS

Type of disaster	Typhoon	Ice	Thunder
MTTR/h	0.6	6.9	0.18

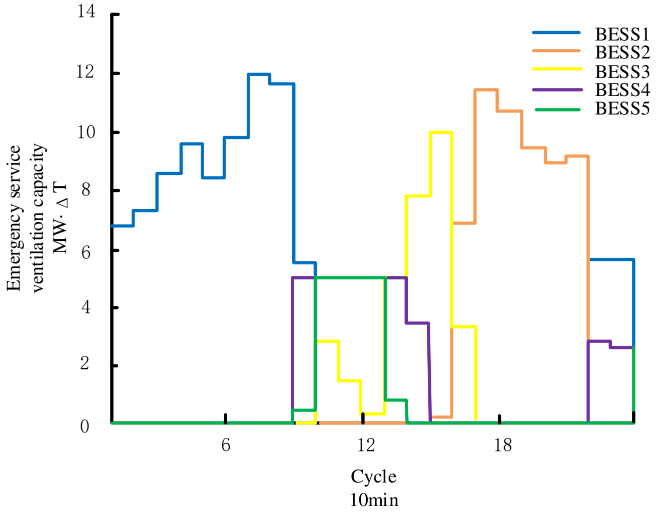
The meantime interval between failures of system components, the continuous available hours of the line and the outage time can be calculated in combination with the historical failure data of the line. These three indicators also fully present the characteristics of the failure risk time interval. Random sampling is performed according to the failure rate distribution curve of the power grid transmission line, and the expected value of the power shortage at node 5 under different scenarios is calculated as shown in Table 3 (duration is 4 hours and every 10min is a calculation cycle).

TABLE 3
EXPECTED VALUE OF ENERGY EXCESSIVE AT NODE 5

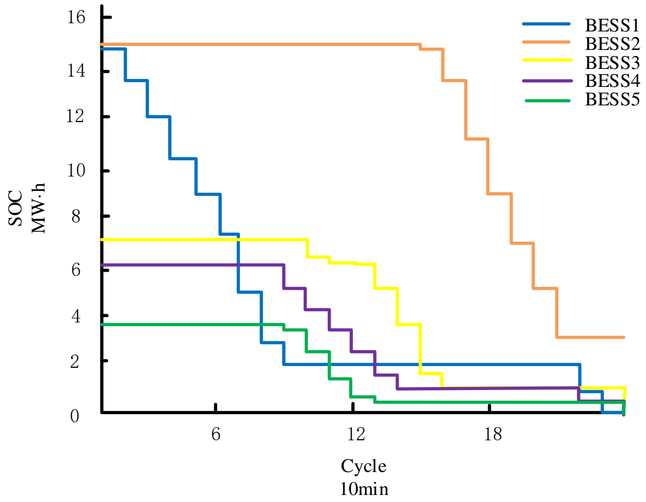
Cycle	Energy excessive	Cycle	Energy excessive	Cycle	Energy excessive
1	6.8MW	9	10.9MW	17	11.4MW
2	7.3MW	10	12.8MW	18	10.7MW
3	8.6MW	11	11.5MW	19	9.4MW
4	9.6MW	12	10.3MW	20	8.9MW
5	8.5MW	13	10.8MW	21	9.1MW
6	9.8MW	14	11.2MW	22	8.6MW
7	12MW	15	10.3MW	23	8.3MW
8	11.7MW	16	10.2MW	24	6.7MW

B. Energy storage clearing capacity

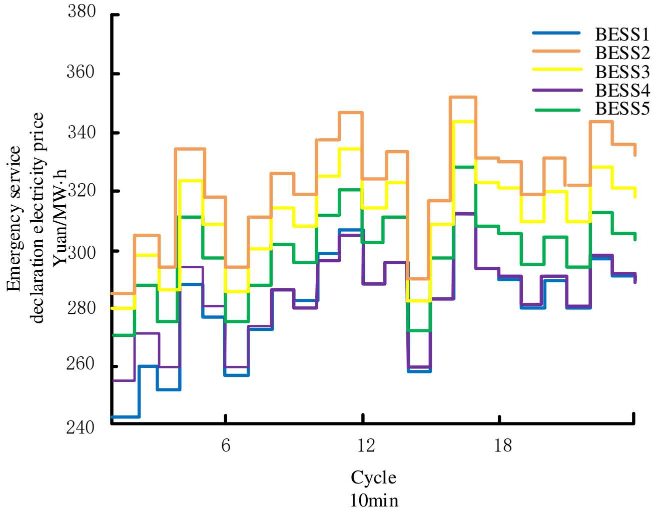
Assuming that the load users of node 5 sign an AEBS agreement with the nearby BESS station, the BESS station must provide AEBS during this period. According to the lowest cost of BESS operation, the clearing results are shown in Figure 3. Among them, it shows the clearing capacity of each BESS station in Figure 3 (a), SOC change curve in Figure 3 (b), and the AEBS declared electricity price in Figure 3 (c).



(a) Schematic diagram of clearing capacity



(b) SOC change curve



(c) Emergency service declaration electricity price

Fig. 6. Clearing result of each energy storage power station.

From the results of Fig.6, only the BESS1 station can effectively clear its reported AEBS capacity t in the cycle 1-8. Low life loss per cycle and high discharge efficiency give its advantage. Its minimum offer is only 241.78 yuan/MW·h, rank first to clear. In the 9th cycle, the BESS4 station and BESS5 station join AEBS array. This is because BESS1 is constrained by the minimum lower limit of SOC and can only provide 5.5MW of power support, while BESS4 station successfully cleared with the second lowest quotation at 279.04 yuan/MW·h. Although the price declared by BESS5 was slightly higher at 294.54 yuan/MW·h, BESS1 and BESS4 alone could not meet the demand, so BESS5 also successfully got clearing capacity.

In cycle 10-13, because of the large power shortage, BESS4 and BESS5 could not meet the demand by providing their maximum power for support, so BESS3 also got clearing capacity. In the 14th cycle, BESS5 was constrained by the minimum capacity and temporarily retired from the emergency backup service array, and BESS2 and BESS3 successfully got clearing capacity. Starting from the 15th cycle, since the maximum power of BESS3 is 10MW and cannot meet the power demand of 10.3MW, BESS2 successfully got the clearing capacity despite the highest declared price. By the 17th cycle, only BESS2 can continue to get clearing capacity at a higher SOC and continue to provide AEBS.

It is noteworthy that from the 22nd cycle; BESS2 is also limited by the minimum capacity and cannot get clearing capacity. The AEBS center had to lower the minimum capacity limit of each BESS station to ensure grid security. Thus, BESS1, BESS4, BESS5 will continue to gain clearing capacity until the grid risk is over.

3) Price analysis

Figure 7 shows the comparison of the clearing prices between the electricity energy market and the AEBS market at the same spot in the same period of the grid.

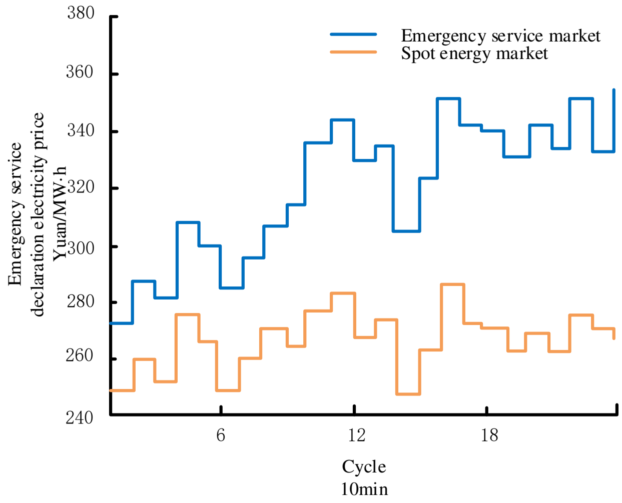


Fig. 7 Comparison of clearing electricity prices in the AEBS market

As seen in Figure 7, the BESS clearing price of the AEBS market is higher than the spot electricity energy market, but the change trend is roughly the same. This is because the opportunity cost, which refers to the benefits of BESS unable to take part in the spot market, mainly affected the price of AEBS. However, besides the opportunity cost, factors such as energy cost and life loss of BESS are also considered when BESS take part in AEBS. That is the reason price of AEBS is higher than the price of the spot electricity energy market. What is more special is that in the 9th cycle, since BESS1, BESS4, and BESS5 all successfully got the clearing capacity, the clearing price is the price declared by the BESS5 station, resulting in a sudden increase in the clearing price. In addition, the 15th cycle, since neither BESS4 nor BESS5 could provide power support, BESS2, which had the highest declared price, was cleared, and the price further increased. Starting from the 22nd cycle, the BESS stations adjust the lower capacity limit under the instruction of the AEBS control center, and it will adjust their quotations in a balanced manner, and the clearing price will also become higher.

TABLE 4

COST OF ENERGY STORAGE POWER STATION IN THE 9TH CYCLE

\	Life loss cost (yuan/MW·h)	Capacity cost (yuan/MW·h)	Market price (yuan/MW·h)
Spot market	\	\	245.74
BESS1	38.01	12.16	281.43
BESS2	28.54	57.81	317.60
BESS3	34.84	40.82	306.90
BESS4	35.63	12.16	279.04
BESS5	37.59	25.69	294.53

Table 4 shows the cost comparison of AEBS provided by all BESS stations in the 9th cycle, assuming that they all get the same support capacity. We can see that the life loss cost of BESS1 and BESS4 is higher, but their high discharge efficiency leads to the lowest capacity cost. The comprehensive market quotation is also lower, ranking front. On the contrary, BESS2 has the lowest life loss cost, but its low discharge efficiency leads to the highest capacity cost. As a result, the market quotation is the highest, and the clearing order is the last.

As shown before, the actual operation BESS1, BESS4, and BESS5 stations successfully got the clear capacity, so the clear price was 294.53 yuan/MW·h.

4) Penalties for failing AEBS after BESS signing contracts

Suppose BESS1 station fails taking part in the AEBS market after signing the contract. In order to ensure the supply of the load as much as possible, the AEBS control center mobilized the nearby temporarily available BESS6 station to take part in the AEBS. It showed the clearing results of BESS stations after the change of market participants in Figure 8-9:

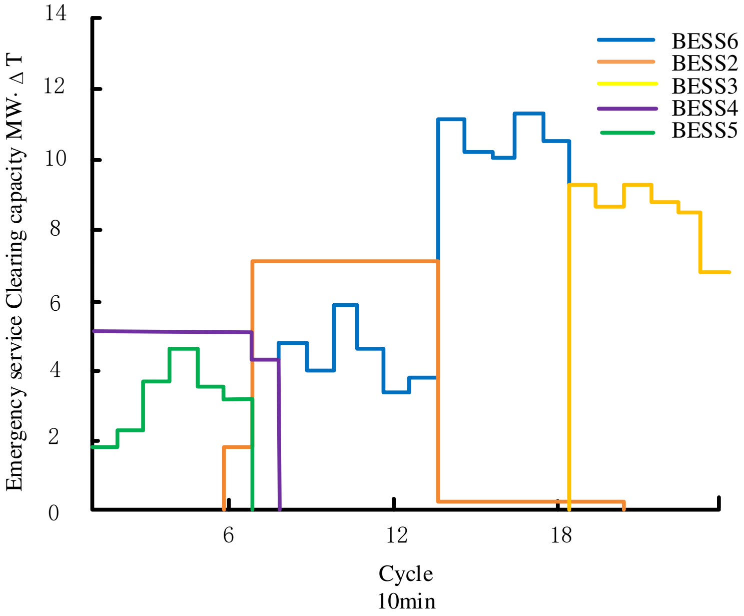


Fig. 8 Clearing capacity of each energy storage power

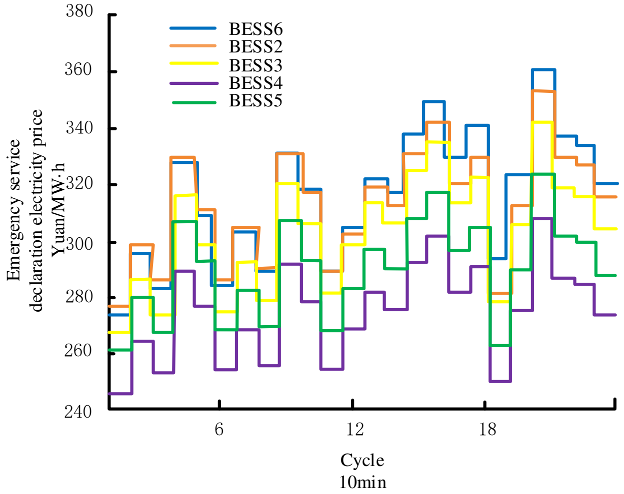


Fig. 9 Emergency backup service electricity prices of various

Comparing Figure 6, it can be seen that the BESS4 and BESS5 stations provide AEBS within the first hour, and the BESS6 station will take part in power support in the 8-18th cycles. Set the penalty coefficient = 0.5, and the total income comparison of BESS operators is shown in Table 5. This penalty mechanism allows the BESS station to withdraw from the AEBS market after signing the contract, but may face a large penalty cost. It also encourages BESS stations to take part in the AEBS market under regulations, providing the grid with promised emergency services.

Table 5 shows settlement of BESS operators' revenue. BESS operator 1 takes part in AEBS in Case1while fails to perform the contract in case2. The comparison is as follows:

TABLE 5
SETTLEMENT OF ENERGY STORAGE OPERATOR REVENUE

case	BESS operator	Revenue /yuan	Total revenue /yuan	Settlement method
1	1	25344	71780	Equation 30
	2	18614		
	3	10038		
	4	11610		
	5	6174		
2	1	-14182	/	Equation 32
	2	25881	75755	Equation 30
	3	17029		
	4	16588		
	5	10435		
	6	58222		

As it can be seen that revenue are calculated using Equation 30 for fulfilled contracts and Equation 32 for unfulfilled contracts. When BESS operator 1 fails to perform the contract, there is no income and 56% of the original contract income will be paid as compensation. This penalty mechanism can curb the occurrence of dishonest behavior in the LMP method.

VII. CONCLUSION

This paper proposes an accurate reserve model based on dynamic risk prediction and BESS as the main reserve resource for extreme events. In addition, this work also build an AEBS (ancillary emergency backup service) market which fully considered characteristics of BESS. Beyond that, the penalty mechanism in the emergency market also effectively curbs dishonest behavior in bidding.

Utilities and ISOs currently rely on rules-of-thumb, deterministic, static, and manual incorporation of probabilistic forecasts when utilizing historical data approaches to determine reserves. The ability to systematically incorporate risk forecasts on the reserve dimensioning will allow them to protect the system against less frequent but potentially more damaging conditions such as adverse weather. Unlike the ancillary services such as frequency regulation, AEBS has the characteristics of short-term, small probability, and dynamic changes in risk.

The case study shows that BESS owners is more profitable in AEBS market than in the real-time balancing spot market while maintaining high, user-specified reliability levels. Additionally, the case also shows BESS's cost and SOC are essential to the clearing order and critical to the profit. In fact, the validity of penalty mechanism is tested by comparing the revenue of contracted with respect to the unfulfilled, with satisfactory results.

This work has certain reference significance for the construction of electric ancillary service market. A desirable next step would be to use the proposed method in a real market environment to measure the reliability improvements and the impacts on cost and other scheduling metrics.

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APPENDIX

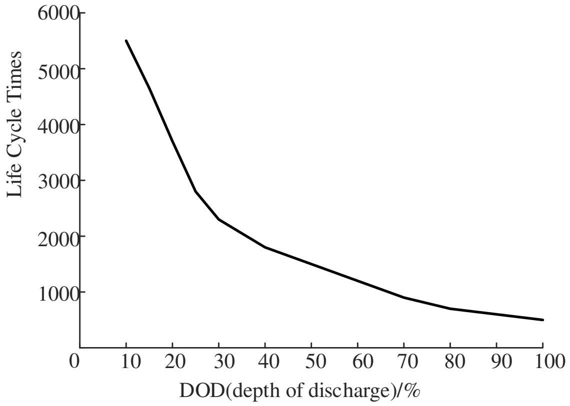

Fig.A1 Relationship between number of life cycle times and DOD

Formula Derivation

$$
\begin{aligned}
L = & \sum_{t\in T}\sum_{i\in I}\frac{r(1+r)^{T_{shelf}}}{(1+r)^{T_{shelf}}-1}\frac{c_i}{YD\frac{60}{\Delta t}}.+\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{energy}P_{i,t}^{cap}(\frac{1}{\beta_i^{dis}}-1)\Delta t+\sum_{t\in T}\sum_{i\in I}(aSOC_{i,t}+bSOC_{i,t-1}+cDCR_{i,t}+d) \\
& +\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{energy,b}P_{i,t}^{cap,b}\Delta t-\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{energy,r}P_{i,t}^{cap,r}\Delta t-\lambda_t^p\Delta t(\sum_{i=1}^{N}P_{i,t}^{\mathrm{cap}}-EENS_i)-\mu_t^{ps}\Delta t(SOC_{i,t}+\frac{P_{i,t}^{cap}\Delta t}{\beta_i^{dis}}-SOC_{i,t-1}) \\
= & \sum_{t\in T}\sum_{i\in I}\frac{r(1+r)^{T_{shelf}}}{(1+r)^{T_{shelf}}-1}\frac{c_i}{YD\frac{60}{\Delta t}}.+\sum_{t\in T}\sum_{i\in I}\lambda_{i,t}^{energy}P_{i,t}^{cap}\frac{1}{\beta_i^{dis}}\Delta t+\sum_{t\in T}\sum_{i\in I}(aSOC_{i,t}+bSOC_{i,t-1}+c\frac{SOC_{i,t-1}-SOC_{i,t}}{\Delta t}+d) \\
& -\lambda_t^p\Delta t(\sum_{i=1}^{N}P_{i,t}^{\mathrm{cap}}-EENS_i)-\mu_t^{ps}\Delta t(SOC_{i,t}+\frac{P_{i,t}^{cap}\Delta t}{\beta_{dis}}-SOC_{i,t-1})
\end{aligned}
\tag{A1}
$$

Table A1 The result of line failure rate

Line		Failure rate	Line		Failure rate	Line		Failure rate
From	To	–	From	To	–	From	To	–
1	2	0.33	4	12	0.36	21	22	0.22
1	3	0.42	12	13	0.24	15	23	0.1
2	4	0.46	12	14	0.31	22	24	0.2
3	4	0.27	12	15	0.22	23	24	0.27
2	5	0.52	12	16	0.24	24	25	0.09
2	6	0.53	14	15	0.19	25	26	0.19
4	6	0.25	16	17	0.25	25	27	0.16
5	7	0.21	15	18	0.1	28	27	0.08
6	7	0.24	18	19	0.2	27	29	0.08
6	8	0.4	19	20	0.23	27	30	0.14
6	9	0.24	10	20	0.27	29	30	0.14
6	10	0.25	10	17	0.27	8	28	0.56
9	11	0.25	10	21	0.33	6	28	0.56
9	10	0.25	10	22	0.25	-	-	-
