A Control Strategy for Battery Energy Storage Systems Participating in Primary Frequency Control Considering the Disturbance Type

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ABSTRACT In power systems, various types of disturbances can randomly affect the active power balance, which can result in unexpected frequency changes. A battery energy storage system (BESS) is an effective technique to assist power system primary frequency control. In this work, a comprehensive self-adaptive strategy considering load disturbance types is proposed that enables BESS participation in the primary frequency control of power grids. First, the different types of load disturbances in the power system are divided into two categories, namely, step disturbance and continuous small disturbance. Then, the advantages of virtual inertia control and virtual droop control are taken into full consideration. Model A and Model B are proposed to match the two load disturbance types. Model A is used to rapidly prevent sudden changes in frequency under step disturbance conditions without restricting the state of charge (SOC) of the BESS. Under the conditions of continuous small disturbances, we further propose Model B in which primary frequency control is realized while considering SOC recovery. Compared with the previous primary frequency control methods, the presented approach significantly improves the stability of complicated and changeable power systems. Meanwhile, it fulfills the frequency control requirements with superior frequency control performance.

INDEX TERMS Adaptive control strategy, battery energy storage system (BESS), disturbance type, primary frequency control, state of charge (SOC).

I. INTRODUCTION

With the rapid development of the economy, urban power grids in economically developed regions are characterized by large capacity, multiple load types, and high load density. Due to the close interconnection of power grids, local load disturbances significantly impact the frequency of the entire power grid [1]. Owing to the fluctuating and uncertain properties of output power from new energy sources, their large-scale energy integration into the grid will significantly increase frequency regulation requirements [2], [3]. To address these problems, the generator capacity reserve, including rotating reserve and cold reserve, is used to realize frequency control in traditional power systems [4]. However, if the backup unit is far from the load center, even a sufficient system reserve backup capacity can hardly guarantee the stability of the power system. In the presence of a large disturbance in power systems, an ordinarily large thermal power unit cannot always meet the climbing requirements. In this case, the only way to maintain system stability is either load shedding or turning off the generator that is unanticipated [5]. A battery energy storage system (BESS) possesses features such as rapid response time, flexibility, and reliability. These features endow it with the capability to quickly offset the unbalanced power generated in the system [6], improving the grid anti-interference ability [7]. When the BESS is used in auxiliary power grid frequency control, it significantly improves the power grid frequency control performance and effectively reduces the frequency control standby of traditional units [8], [9]. In this case, a reasonable control strategy...
will improve the BESS frequency control performance and effectively reduce the capacity configuration of the energy storage power supply [10].

The initial stage of BESS participation in primary frequency control research is mainly feasibility studies and control technology. At this time, the control method is concentrated on droop control [11], [12]. Droop control is similar to the proportional control of the generator set speed control system, which can effectively reduce the quasi-steady state frequency deviation [5]. Load diversity, new energy access to the power grid, and the application of microgrids have caused corresponding changes in the frequency control requirements of traditional power grids [13], [14]. Owing to the above factors, the inertia constant of the traditional power system is reduced. The frequency stability of low-inertia power grids will be more likely to be threatened by uncertain disturbances [15], [16]. In order to solve this problem, [17] proposed a new frequency control strategy based on virtual synchronous generator including virtual inertia control. A fast response virtual synchronous machine technology based on superconducting magnetic energy storage technology is proposed. It can simulate the required inertial power in a short time, so that the system frequency can be stabilized under different disturbances [18]. Based on Ref. [17], [18], the author uses the remaining energy storage (electric vehicle) in the existing system to simulate the inertia of the power system, and further proposes a new integrated inertial control system to enhance the frequency stability of the system [19]. Essentially, virtual inertial control is based on differential control and can respond immediately to frequency changes in the initial state. By using a virtual inertial control strategy for energy storage, the BESS can effectively suppress the rate of change of the maximum frequency deviation and alleviate the speed of frequency change [20], [21].

However, a single control strategy cannot always satisfy the frequency control requirements of modern power grids. Virtual droop control can reduce the quasi-steady state frequency deviation but cannot suppress the frequency change speed. Virtual inertial control plays a role in the process of frequency change but cannot reduce the quasi-steady state frequency deviation. To make full use of the advantages of virtual droop control and virtual inertial control, an increasing number of studies combine droop control and inertial control to form a combined control method of primary frequency control [20], [22]–[26]. In Ref. [26], the authors combined the advantages of two control strategies by using the point of time when the maximum frequency deviation is reached as the switching boundary. Energy storage uses virtual inertial control when the frequency drops and converts to virtual droop control when the frequency is restored. The results show that the combined control method has a better frequency control effect than the single control method. However, the calculations involved in this approach are complicated in practical situations and difficult to apply to continuous load disturbance conditions.

Recently, research on BESSs participating in primary frequency control has mainly focused on enhancing the frequency stability of power systems and improving the operating economy of BESSs. Some studies use BESS to simulate the working principle of traditional generator sets with the goal of improving the frequency control effects [12], [27]. In the long-term participation of BESSs in the primary frequency control of the power grid, some studies have considered that different SOC operating expectations will affect the economics of BESSs [28], [29]. Therefore, the primary frequency control capability of BESSs is restricted or the SOC is restored to increase the energy storage life and improve the economics [27], [28], [30]. Their basic idea is to restore the SOC with lower power within the frequency dead zone of the power system. The purpose is to reduce the negative impact of the depth of charge and discharge on the grid while maintaining the SOC to extend the service life of battery energy storage. In Ref. [31], the authors proposed a probability prediction algorithm in the primary frequency control of energy storage systems to quantitatively calculate the SOC under random frequency deviation. References [32] and [33] proposed using SOC as the feedback variable of the primary frequency modulation output coefficient. This method takes into account the capacity limitation of battery energy storage and treats it differently from conventional frequency modulation power supplies. It can improve the SOC operating state while meeting the performance of primary frequency modulation. However, when the SOC is too high or too low, the ability of energy storage to participate in grid frequency control will be either reduced or become nonexistent.

In this article, On the one hand, we focus on a comprehensive control strategy to meet the different frequency control requirements caused by different load disturbances. On the other hand, our work takes into account long-term economic operation while energy storage completes the task of frequency control. To achieve good primary frequency control performance under different working conditions, we propose an adaptive strategy for BESSs that can participate in the primary frequency control of grids and take into account different types of load disturbances. The main contributions of this article are as follows:

1. The control method of energy storage frequency control is comprehensively analyzed in detail, which can be used as the basis of the control strategy in this article.

2. The different types of load disturbances in the power system are divided into two categories. Models A and B are proposed to match the two load disturbance types. Model A proposes that BESS can rapidly prevent frequency deterioration in the case of a step disturbance. Under continuous disturbance, Model B for the BESS enables SOC recovery and improves both the frequency control performance and battery life.

3. This strategy considers different frequency control requirements caused by different types of disturbances. This provides a new guide for BESSs to participate in primary
frequency control, which can be used by different types of BESSs.

II. BASIC CONTROL METHOD OF ENERGY STORAGE FREQUENCY CONTROL

Power system primary frequency control can adjust the system frequency by using the static frequency characteristics of the system load and the generator unit. The inertia effect of the generator rotor and the damping effect of the load can mitigate the system frequency change. At the same time, the governor of the prime mover will automatically change the air inlet valve of the prime mover, consequently modifying the active power output to achieve frequency adjustment [34]. The BESS participates in the primary frequency control of power grids by simulating the primary frequency control characteristics of the synchronous generator. It simulates the drooping characteristic of the generator governor through the virtual droop control mode and adjusts the frequency deviation. Similarly, it uses a virtual inertial control model to simulate the moment of inertia of the generator rotor, which can effectively slow the frequency change rate.

Taking the frequency drop caused by the load increase as an example, the frequency deviation curve and frequency change rate curve of the whole process of power system frequency control are shown in Fig. 1 and Fig. 2, respectively. The system frequency drops sharply to the minimum value \( f_{\min} \) in the degradation stage \( (t_0 \sim t_m) \); that is, the absolute value of the frequency deviation \( |\Delta f(t)| \) at \( t_m \) changes from 0 to the maximum value \( |\Delta f_{\min}| \). At the same time, the absolute value of the frequency change rate \( |\Delta \omega (t)| \) is reduced from the maximum value to 0. In the rebound stage \( (t_m \sim t_s) \), the system frequency rises from \( f_{\min} \) to the quasi-steady state value \( f_{qs} \), and \( |\Delta f(t)| \) is reduced to \( |\Delta f_s| \). \( |\Delta \omega (t)| \) increases from 0 and then gradually decreases and approaches 0. In the recovery phase (second frequency control), \( |\Delta f(t)| \) gradually decreases and finally returns to the rated value \( f_0 \), while \( |\Delta \omega (t)| \) fluctuates around 0.

The power system is a complex nonlinear dynamic system. It is unrealistic to try to build a model that reflects all the characteristics of the system. Modeling should be based on the scope and content of the research and reflect the system characteristics closely related to the research purpose as much as possible. As shown in Figs. 3-5, we analyze the influence of two control modes of virtual inertia and virtual droop on the frequency characteristics in the frequency domain of regional power grids [1], [23], [31], [33]–[36].

A. VIRTUAL DROOP CONTROL

The control of the energy storage power converter can simulate the drooping characteristics of the traditional frequency control unit. As a result, virtual droop control that can participate in primary frequency control can be realized. Virtual droop control is applied to the BESS in which the nonlinear components of the generator and energy storage are ignored. Fig. 3 shows that BESS uses virtual droop control to participate in the primary frequency control of the regional grid. (1) and (2) describe the relationship between the variables shown in Fig. 3:

\[
\begin{align*}
\Delta P_G(s) &= -K_G \cdot G(s) \cdot \Delta F(s) \\
\Delta P_B(s) &= -K_B \cdot B(s) \cdot \Delta F(s) \\
\Delta P_G(s) + \Delta P_B(s) - \Delta P_L(s) &= \Delta F(s) (2Hs + D)
\end{align*}
\]
synchronous generator. $K_G$ is the unit regulation power of conventional units, and $K_B$ represents the virtual droop control coefficient. The traditional units and energy storage transfer function are represented as $G(s)$ and $B(s)$, respectively. According to [1], the power conversion system (PCS) can be equivalent to the first-order inertia for frequency control. The expressions for $G(s)$ and $B(s)$ are given as:

$$G(s) = \frac{1 + F_{HP}T_{RH} \cdot s}{(1 + T_G \cdot s)(1 + T_{CH} \cdot s)(1 + T_{RH} \cdot s)} \quad (3)$$

$$B(s) = \frac{1}{1 + T_{PCS} \cdot s} \quad (4)$$

where $T_G$, $T_{CH}$, and $T_{RH}$ are the governor, steam chest and, reheat turbine time constants, respectively. The high-pressure power fraction of the reheat turbine is given by the $F_{HP}$, and $T_{PCS}$ is the time constant of the PCS.

Based on the above equations, the system frequency can be expressed as follows:

$$\Delta F(s) = \frac{-\Delta P_L(s)}{K_G \cdot G(s) + K_B \cdot B(s) + 2H \cdot s + D} \quad (5)$$

According to the initial and final value theorems of the Laplace transform, we obtain the following expressions:

$$\begin{align*}
df_0 &= \lim_{s \to \infty} s \cdot [s \cdot \Delta F(s)] = -\Delta P_L \frac{2H}{2H + D} \\
\Delta f_s &= \lim_{s \to 0} s \cdot \Delta F(s) = -\frac{\Delta P_L}{K_G + K_B + D}
\end{align*} \quad (6)$$

where $df_0$ and $\Delta f_s$ are the initial frequency difference change rate and the quasi-steady state frequency deviation value, respectively. The step load disturbance amplitude value is denoted by $\Delta P_L$.

It can be seen from (6) that $df_0$ is independent of the energy storage droop control and is only related to $H$. On the other hand, $\Delta f_s$ is inversely proportional to $K_B$. In the presence of a load change, the larger the energy storage droop coefficient, the smaller the steady state frequency deviation.

It can be observed from (1) that the BESS output is proportional to the system frequency deviation. At the initial stage of load disturbance, the system frequency deviation is either 0 or close to 0, and the BESS output is either 0 or very small. As the system frequency deviation increases, the BESS frequency control output increases as well. Therefore, the frequency control of the BESS has hysteresis at this time. When the sum of the output of the BESS and the generator exceeds $\Delta P_L(s)$, $\Delta F(s)$ begins to decrease and stabilizes at $\Delta f_s$. At this time, this sum is equal to $\Delta P_L(s)$, and the expressions of the output of BESS and the generator are given as (7).

$$\begin{align*}
\Delta P_{Gs} &= \frac{K_G}{K_G + K_B + D} \Delta P_L \\
\Delta P_{Bs} &= \frac{K_B}{K_G + K_B + D} \Delta P_L
\end{align*} \quad (7)$$

B. VIRTUAL INERTIA CONTROL

Similar to Fig. 3, any nonlinear components of the generator and energy storage are ignored. Fig. 4 shows that the BESS uses virtual inertia control to participate in the primary frequency control of the regional grid, where $M_B$ is defined as the virtual inertia control coefficient.

It can be noted from Fig. 4 that the virtual inertia output of the BESS is:

$$\Delta P_B(s) = -(s \cdot M_B \cdot s \cdot \Delta F(s)) = -B(s) \cdot M_B \cdot dF(s) \quad (8)$$

Similar to (5) and (6), the following equations can be obtained:

$$\begin{align*}
df_0 &= \lim_{s \to \infty} s \cdot [s \cdot \Delta F(s)] = -\Delta P_L \frac{2H}{2H + M_B} \\
\Delta f_s &= \lim_{s \to 0} s \cdot \Delta F(s) = -\frac{\Delta P_L}{K_G + M_B + D}
\end{align*} \quad (9)$$

It can be seen from (10) that $df_0$ is inversely proportional to $M_B$. When the load changes to a fixed value, the larger the energy storage inertia coefficient is, the smaller the initial frequency deviation rate. On the other hand, $\Delta f_s$ is independent of the energy storage inertia control. It can be noted from (8) that the output of the BESS is proportional to the rate of change of the frequency deviation, and the rate of change of the system frequency deviation is the largest at the initial moment of disturbance. The system frequency begins to decrease when the load disturbance is positive, and the energy storage system and generator will start to output power. The output of BESS at the initial moment is (11).

$$\Delta P_{B0} = \frac{M_B}{2H + M_B} \Delta P_L \quad (11)$$

This output of the BESS and generator will reduce the rate of change of the system frequency deviation, which in turn decreases the output of the BESS. When the sum of the output of the BESS and the generator exceeds the load disturbance, the system frequency begins to recover instead of continuously decreasing, and the rate of change of the system frequency deviation is positive. At this time, the output of the BESS is negative according to (8), i.e., the BESS output is adjusted in reverse, which hinders the system frequency recovery. In the end, the system frequency deviation shown in (10) is obviously not related to the energy storage system.
C. COMBINATION CONTROL STRATEGY

According to the analysis results of the virtual droop control and virtual inertia control in section A and section B, two conclusions can be drawn: 1) virtual droop control can effectively reduce the absolute value of $\Delta f_m$ and $\Delta f_s$, but it has no effect on $\Delta \omega$; 2) virtual inertia control has a positive effect on $\Delta f_m$ and $\Delta \omega$ but has no effect on $\Delta f_s$. Therefore, combining the advantages of virtual droop control and virtual inertia control can make full use of BESS to improve the frequency control effects. The combined control of the BESS to participate in the primary frequency control of the regional grid is shown in Fig. 5.

Similarly, (12) can be obtained from Fig. 5.

$$\Delta F(s) = \frac{-\Delta P_L(s)}{K_G \cdot G(s) + (M_B \cdot s + K_B) \cdot B(s) + 2Hs + D}$$

Then, the transfer function of load disturbance and grid frequency deviation is (13).

$$H(s) = \frac{\Delta F(s)}{-\Delta P_L(s)} = \frac{1}{K_G \cdot G(s) + (M_B \cdot s + K_B) \cdot B(s) + 2Hs + D}$$

In the same way, the transfer functions of Fig. 3-Fig. 4 and the system without BESS can be calculated, as shown in (14)-(16).

$$H_1(s) = \frac{1}{K_G \cdot G(s) + K_B \cdot B(s) + 2Hs + D}$$

$$H_2(s) = \frac{1}{K_G \cdot G(s) + M_B \cdot s \cdot B(s) + 2Hs + D}$$

$$H_3(s) = \frac{1}{K_G \cdot G(s) + 2Hs + D}$$

The reasonable requirement range of load disturbance within the range of stable system frequency is (17).

$$-\Delta P_L(s) \cdot H(s) = \Delta F(s) \Rightarrow |\Delta P_L(s)| \leq \frac{|\Delta F(s)|}{H(s)}_{\text{max}}$$

A Bode diagram was used to analyze the amplitude-frequency characteristics of equations (13)-(16), as shown in Fig. 6, and the parameters are shown in Table 1. From Fig. 6, the maximum load disturbance that the grid can bear is obtained by analyzing its amplitude-frequency characteristics.

It can be clearly seen from Fig. 6 that the maximum amplitude of the amplitude-frequency characteristic is 0.12 p.u. when the power grid is without a BESS. If the maximum allowable frequency deviation of the power grid is 1% (1 p.u.) of the rated frequency (50 Hz), that is, the frequency deviation is ±0.5 Hz. Therefore, according to (17), the maximum load disturbance amplitude is 8.3% in the power grid without BESS. Similarly, when BESS uses virtual inertia control to participate in the primary frequency control, the maximum amplitude is 10.87%; when it adopts virtual droop control, the maximum amplitude is 26.32%; and when it adopts the combination control strategy, the maximum amplitude is 31.25%.

In summary, the participation of a BESS in grid frequency control can effectively improve the anti-interference ability of the grid. When the BESS adopts the combination control strategy, the anti-interference ability of the grid is improved by approximately 4 times compared to that without energy storage.

III. COMPREHENSIVE SELF-ADAPTIVE STRATEGY OF BESS FOR PRIMARY FREQUENCY CONTROL

This article considers the case of an emergency in the power grid, such as a sudden tripping of the generator or a sudden increase in load, followed by the return of the system...
Such accidents can cause a large unbalanced active power in the power grid, leading to large system frequency fluctuations, defined as step disturbances. Continuous disturbances such as new energy grid-connected outputs are not constant. Small and long-term frequency changes caused by small load switching and new energy are defined as continuous small disturbances [37]. These two different types of disturbances have different effects on the grid frequency. So the frequency deviation and the frequency change rate can be used to determine the type of disturbance.

The frequency deviation rate curves corresponding to two different disturbances are shown in Fig. 7. Under the step disturbance condition, $|\Delta \omega|$ appears to be a maximum at the initial moment of frequency control. Subsequently, $|\Delta \omega|$ gradually reduces to 0. Under continuous disturbance conditions, $|\Delta \omega|$ fluctuates around 0. Therefore, the disturbance type can be determined according to the value of the frequency deviation change rate, as shown in (18).

The empirical value determined according to the actual operation of the regional power grid is denoted by $\Delta \omega_{\text{ref}}$. A value of flag = 1 indicates that a step disturbance is encountered.

$$ \left\{ \begin{array}{l} \Delta \omega(t) = \frac{f_i - f_{i-1}}{\Delta T} \\ \Delta \omega(t) \geq \Delta \omega_{\text{ref}}, \quad \text{flag} = 1 \\
\Delta \omega(t) < \Delta \omega_{\text{ref}}, \quad \text{flag} = 0 \end{array} \right. \quad (18) $$

where $f_i$ is the system frequency at the current moment, $f_{i-1}$ represents the frequency at the previous sampling moment, and $\Delta T$ represents the sampling time interval.

The energy storage system monitors the system frequency $f_i$ in real time. The BESS participates in grid frequency control when it is found that the deviation between $f_i$ and the rated frequency $f_0$ exceeds the maximum frequency deviation $f_{\text{low}}$ of the grid. When the energy storage system encounters a sudden frequency change, the primary issue to be resolved is the restoration of frequency to a reasonable range rather than maintaining and recovering the SOC of the BESS.

However, considering the economic benefits of the energy storage power supply and to prolong the service life of the energy storage in the absence of step disturbance, the SOC of the energy storage power source should be considered while considering the frequency control effect. Therefore, a comprehensive self-adaptive primary frequency control strategy considering the type of grid disturbance is proposed. On the one hand, this strategy can rapidly identify frequency deviation and recover the frequency in the presence of a large step disturbance in the grid. On the other hand, based on the SOC of the BESS, it can help extend the battery lifetime [34], [38], [39].

Considering the load disturbance types, a comprehensive self-adaptive strategy is proposed that enables BESS participation in primary frequency control of the power grid. The flowchart of the adaptive control strategy of the BESS is shown in Fig. 8. First, the different types of load disturbances in the power system are divided into two categories. Then, the advantages of virtual inertia control and virtual droop control are taken into full consideration. Models A and B are proposed to match the two load disturbance types. In the step disturbance case, the self-adaptive strategy switches to Model A (as shown in Fig. 10), and the energy storage SOC is not considered for the goal of quickly suppressing the sudden frequency change. In the continuous small disturbance case, it will switch to Model B (as shown in Fig. 12) in which the
energy storage can complete self-recovery while adjusting the frequency.

In Fig. 8, the discrimination coefficients \( \delta \) and \( de \) are shown in (19) and (20), respectively. \( \delta \leq 0.001 \) indicates that the system frequency reaches the quasi-steady state after the step disturbance. \( de = 1 \) means that the system frequency deviation and SOC are within a reasonable range.

\[
\delta = \frac{f_i - f_{i-1}}{f_i} \tag{19}
\]

\[
de = \begin{cases} 
1, & |\Delta f| \leq f_{\text{low}} \& SOC_{\text{min}} \leq SOC \leq SOC_{\text{max}} \\
0, & \text{else}
\end{cases} \tag{20}
\]

**Model A: Adaptive control strategy for primary frequency control without considering SOC**

When a step disturbance occurs in the power grid, the system frequency will immediately deteriorate. The BESS should not consider its own SOC and make every effort to prevent frequency deterioration and restore it to a quasi-steady state as soon as possible [38]. Considering the aforementioned frequency response characteristics of virtual droop and virtual inertia, we proposed a reasonable and effect control model (Model A). In the degradation stage, the control strategy adopts virtual inertia as the dominating strategy and virtual droop as an assistant. In the rebound stage, the virtual inertia is exited, and the virtual droop is left. The flowchart of Model A is shown in Fig. 10.

In the degradation stage, the corresponding energy storage output \( P_E \) is given as:

\[
P_E = - \left( a_1 \cdot M_B \cdot \frac{d \Delta f(t)}{dt} + a_2 \cdot K_B \cdot \Delta f(t) \right)
\]

\[
\begin{align*}
& a_1 + a_2 = 1 \\
& a_1 = \max(e^{-|\Delta f(t)|\cdot n}, 0.5)
\end{align*}
\]

As shown in Fig. 9, where \( a_1 \) and \( a_2 \) represent the distribution ratio coefficients of the virtual inertia control and the virtual droop control, respectively. \( a_1 \) and \( a_2 \) are related to the variable speed parameter \( n \), which should be adapted to the changes of \( \Delta f(t) \) and \( \Delta \omega(t) \). If \( n \) is too small, even if \( |\Delta f(t)| \) increases significantly, the changes in \( a_1 \) and \( a_2 \) are not obvious. At this time, \( a_1 \) is still close to 1, and \( a_2 \) is close to 0. However, in reality, when \( |\Delta f(t)| \) is large, \( |\Delta \omega(t)| \) is actually relatively small, so according to (21), the energy storage inertial response and droop response are both small. As a result, with increasing maximum frequency deviation (\( f_{\text{min}} \)), the maximum output of the energy storage will increase. If \( n \) is too large, as long as \( |\Delta f(t)| \) increases slightly, \( a_1 \) will decrease sharply, and \( a_2 \) will increase sharply. \( |\Delta f(t)| \) at the initial moment is small, but \( |\Delta \omega(t)| \) is the largest. Therefore, the decrease in \( a_1 \) makes the energy storage inertial response not fully utilized, and \( |\Delta \omega(t)| \) cannot be minimized. At the same time, the droop response of energy storage must be relatively small. In our previous work, we reported that the frequency control effect is optimized when \( n = 10 \) [20].

The energy storage output \( P'_E \) in the rebound stage of Model A is given as:

\[
P'_E = -K_B \cdot \Delta f(t) \tag{22}
\]

**Model B: BESS primary frequency control strategy considering SOC recovery**

For a continuous small disturbance, the SOC of the BESS is a pivotal parameter during frequency control. It can affect not only the lifetime of BESSs but also the output ability of BESSs [27], [30], [32], [41]–[43]. Model B participates in power grid primary frequency control considering SOC recovery and is proposed to prolong the service life of energy storage, which is shown in Fig. 12. When \( SOC_{\text{min}} < SOC < SOC_{\text{max}} \), Model B will perform frequency control and restore the SOC at the same time. If \( SOC \leq SOC_{\text{min}} \) or \( SOC \geq SOC_{\text{max}} \), it will restore the SOC without frequency control. A combination of virtual droop control and virtual inertia control was used in the two stages of primary frequency control. The frequency control power of BESS is:

\[
P_E = \begin{cases} 
P'_b, & SOC \leq SOC_{\text{min}}, SOC \geq SOC_{\text{max}} \\
K_p P'_b, & SOC_{\text{min}} < SOC < SOC_{\text{max}}
\end{cases}
\tag{23}
\]

where \( P'_b \) indicates the energy storage SOC recovery power, \( P'_b \) is the output of energy storage for frequency control, \( K_p \) is the penalty factor, and \( SOC_{\text{max}} \) and \( SOC_{\text{min}} \) represent the maximum and minimum values of the SOC, respectively. When \( SOC \leq SOC_{\text{min}} \) or \( SOC \geq SOC_{\text{max}} \), the energy storage SOC should be restored, and its participation in the power grid frequency control should be suspended. When \( SOC_{\text{min}} < SOC < SOC_{\text{max}} \), the energy storage can participate in the power grid frequency control. However, to solve the conflict between frequency control and energy storage recovery, a penalty coefficient \( K_p \) is introduced, which is
deviation of the system. In the dead zone, the system frequency is within a reasonable range, and $K_p$ decreases as the frequency deviation increases.

$$P_{br}^e = P_{br}^m + P_{br}^{rd}$$  \hspace{1cm} (25)

$$P_{br}^f = -(M_B \cdot \frac{d\Delta f(t)}{dt} + K_B \Delta f(t))$$  \hspace{1cm} (26)

In the above equations, $P_{br}^m$ is the charge recovery power and $P_{br}^{rd}$ is the discharge recovery power. Their values are defined as follows:

1) When $0 \leq SOC \leq SOC_{min}$, $P_{br}^d = 0$, $P_{br}^e = -P_{br}^m$;
2) When $SOC_{min} < SOC \leq SOC_0$, $P_{br}^d = 0$, $P_{br}^e = -P_{br}^m \cdot \sqrt{1 - \left(\frac{SOC - SOC_{min}}{SOC_0 - SOC_{min}}\right)^2}$;
3) When $SOC_0 < SOC \leq SOC_{max}$, $P_{br}^d = P_{br}^m \cdot \sqrt{1 - \left(\frac{SOC - SOC_{max}}{SOC_0 - SOC_{max}}\right)^2}$, $P_{br}^e = 0$;
4) When $SOC_{max} < SOC \leq 1$, $P_{br}^d = P_{br}^m$, $P_{br}^e = 0$;

where $P_{br}^m$ is the maximum value of the energy storage recovery power. To reduce the frequency oscillation caused by $P_{br}^m$, $P_{br}^{rd}$ cannot be too large; otherwise, even when the frequency is stable, it may cause the system frequency to fall out of the dead zone. To ensure that the system frequency does not fall out of the dead zone $\Delta f_d$, condition (27) must be met.

$$|\Delta f| \leq \Delta f_d$$  \hspace{1cm} (27)

According to (6) and (27), $P_{br}^m$ can be expressed as:

$$P_{br}^m \leq (K_G + K_B + D)\Delta f_d$$  \hspace{1cm} (28)

In the actual frequency control process, the synchronous generator does not work in the dead zone, and the energy storage system can accurately control the power through the PCS, so $P_{br}^m$ can be expressed as:

$$P_{br}^m = (K_B + D)\Delta f_d$$  \hspace{1cm} (29)

Feasibility of the switch between Model A and Model B

There are two situations between Model A and Model B: Model A switches to Model B or Model B switches to Model A.

1) MODEL A SWITCH TO MODEL B

The process of Model A is that BESS does not consider the limitation of SOC to prevent frequency deterioration until the frequency returns to a quasi-steady state. BESS exits when primary frequency control finished. After that, assuming that the grid immediately encounters continuous small disturbances, the BESS will automatically switch to Model B, that is, Model A will switch to Model B. The output of Model B is shown in (23).

At this time, Model B will first judge whether the energy storage is suitable for primary frequency control. Case 1): If
the SOC is unreasonable after Model A switches to Model B (SOC ≤ SOC\textsubscript{min} or SOC ≥ SOC\textsubscript{max}), the BESS will give up frequency control and automatically restore the SOC to SOC\textsubscript{min} or SOC\textsubscript{max}. Then, enter the situation of case 2). Case 2): If the SOC after Model A switch to Model B is reasonable (SOC\textsubscript{min} < SOC < SOC\textsubscript{max}), the BESS will directly participate in frequency control until the system frequency and energy storage SOC are both within a reasonable range. On the one hand, \( K \) which is shown in (24), limits the recovery power when recovering the SOC while frequency control. On the other hand, as shown in (27-29), \( P^r_e \) ensures that the system frequency does not fall out of the dead zone. In both cases, 1) and 2), the smoothness of the switching is taken into consideration. The switching from Model A to Model B is handled appropriately, so it will not cause additional interference to the grid.

(2) MODEL B SWITCH TO MODEL A
Assuming that the continuous small disturbance of the system suddenly becomes a step disturbance, the system will determine that it is necessary to switch from Model B to Model A. To cope with the sudden increase or decrease in the frequency deviation, Model B maintains the SOC of the BESS at 0.5. In this way, it can be satisfied whether charge or discharge is needed during the Model B switch to Model A. When encountering step disturbances, the energy storage output of Model A is unlimited. In this state, the energy states of the battery and the grid are complementary, so energy storage can be directly used in the grid without considering continuity.

To sum up (1) and (2), the switch between Model A and Model B will not add additional disturbance to the system. Therefore, the switch between them is feasible and smooth.

IV. SIMULATIONS
A. EVALUATION INDICES OF FREQUENCY CONTROL
In this paper, time-domain indices are used to evaluate the performance of BESS participation in primary frequency control. These indices include frequency control effect indicators and SOC indicators, which are described in the following paragraphs.

1) FREQUENCY CONTROL EFFECT INDICATORS
The initial and maximum deviation values of the grid frequency are denoted by \( \Delta f_0 \) and \( \Delta f_m \), respectively, \( \Delta f_i \) is the deviation value of the grid frequency in the quasi-steady state, and \( f_{\text{rms}} \) is the root mean square value of the frequency deviation, as shown in (30):

\[
f_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\Delta f_i - \Delta f_0)^2}
\]

where \( i \) represents the sampling point and \( N \) is the total number of sampling points. A smaller value of \( f_{\text{rms}} \) indicates a better BESS performance.

The frequency drop rate \( V_m \) is shown as follows:

\[
V_m = |(\Delta f_0 - \Delta f_m) / (t_0 - t_m)|
\]

where \( t_0 \) and \( t_m \) are the initial time and the time corresponding to the maximum deviation of the grid frequency, respectively.

The frequency recovery speed \( V_r \) is given in (32).

\[
V_r = |(\Delta f_i - \Delta f_m) / (t_i - t_m)|
\]

In the above equation, \( t_i \) is the time corresponding to the deviation value in the presence of quasi-steady state grid frequency.

2) SOC INDICATOR
The indicator of the SOC of BESS (SOC\textsubscript{rms}) is expressed as:

\[
\text{SOC}_{\text{rms}} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\text{SOC}_i - \text{SOC}_0)^2}
\]

where \( \text{SOC}_i \) is the SOC at the \( i \)-th sampling point. The closer the value of \( \text{SOC}_{\text{rms}} \) is to the value of \( \text{SOC}_0 \), the better the stability effect of the SOC.

B. COMPARATIVE METHODS IN REFERENCES
1) METHOD 1
Droop control is the most commonly used control strategy for BESSs to participate in frequency control of the power grid, and it is suitable for almost all types of battery energy storage. To improve the effect of frequency control and maintain the SOC of battery energy storage, some current representative studies have introduced an SOC equalization strategy in droop control, that is, battery SOC maintenance (Battery SOC Holder, BSH strategy) \[2], \[29], \[33], \[44]. The output power of battery energy storage using the variable coefficient droop control method can be described as (34):

\[
P_E = K \cdot (\text{SOC}) \cdot \Delta f \leq P_{B_{\text{max}}}
\]

where \( P_{B_{\text{max}}} \) is the limit constraint of the maximum output of energy storage and \( K(\text{SOC}) \) is the droop control coefficient, which is a function of SOC.
In [29], a control scheme is proposed that considers charging requests for the next user and battery conditions. This strategy adopts droop control and automatically adjusts the droop coefficient according to the SOC state of the electric vehicle. Finally, the output of the BESS is designed according to the frequency deviation and its own SOC as follows:

\[ P_E = \begin{cases} K_E \cdot |\Delta f|, & |K_E \cdot |\Delta f| | \leq P_{\text{max}} \\ P_{\text{max}}, & P_{\text{max}} < |K_E \cdot |\Delta f| \end{cases} \tag{35} \]

where

\[ K_E = K_{\text{max}} \left( 1 - \left( \frac{SOC(t) - SOC_{\text{low(high)}}}{SOC_{\text{max(min)}} - SOC_{\text{low(high)}}} \right)^n \right) \tag{36} \]

where \(SOC_{\text{min}}, SOC_{\text{low}}, SOC_{\text{high}}, SOC_{\text{max}},\) and \(n\) are parameters and \(SOC_{\text{min}}, low, high, max = 10, 20, 80, 90\) (\%), \(n = 2\). \(n\) is designed as the SOC is balanced approximately 50%. The method adjusts the droop coefficient according to the value of the SOC. This adjustment changes the degree of battery energy storage participation in grid frequency control. When the SOC is too high or too low, the charging and discharging droop coefficient is small. Consequently, the ability of the energy storage system to participate in power grid frequency control either becomes too low or even ineffectual.

2) METHOD 2

An energy storage system capacity allocation method is proposed in [26]. The complex frequency domain sensitivity principle is used to analyze the frequency characteristics of the power grid with energy storage, and then a comprehensive control mode including virtual inertia control and virtual droop control is proposed. Based on time-domain sensitivity analysis, virtual inertia control is entered at \(t_0\), the two control modes are switched when the frequency change rate crosses zero, and virtual droop control exists at \(t_1\). The control coefficients of virtual inertia and virtual droop are determined according to the requirements of the frequency control evaluation indices. Finally, a method of energy storage capacity configuration is formed, and the output of energy storage is:

\[ P_E = \begin{cases} M_B \cdot \frac{d\Delta f}{dt}, & \frac{d\Delta f}{dt} < 0 \\ K_B \cdot \frac{d\Delta f}{dt}, & \frac{d\Delta f}{dt} > 0 \end{cases} \tag{37} \]

The model takes into account the advantages and disadvantages of virtual inertia control and virtual droop control. The experimental results also prove that Method 2 has indeed achieved the better effect of frequency control. Notably, this method does not consider the situation where the system encounters continuous small disturbances. At this time, the frequency will continue to change randomly, so the energy storage system may switch continuously between virtual inertia control and virtual droop control.

C. SIMULATION EXPERIMENTAL RESULTS

To verify the effectiveness of the proposed method, three different conditions are used to test the dynamic frequency modulation performance of the BESS, namely, step disturbance, long-term small continuous disturbance and load disturbance of the combined step and continuous disturbance. Different control strategies (present method, Method 1 and Method 2) were used for the detailed comparison and discussion under the same working conditions. All control strategies and working conditions are realized by MATLAB/Simulink software platform. It should be noted that the load disturbance \(\Delta P_L(s)\) in the simulation is a comprehensive disturbance of the regional power grid. That is, the sum of the load power change and the power change of the grid-connected new energy. The primary frequency control structure of the regional power grid with BESS is shown in Fig. 13, and the parameters are shown in Table 1 [34]. The present method, Method 1 and Method 2 are used in the control strategy module of Fig. 13.

1) CONDITION 1. STEP DISTURBANCE

The simulation is based on a typical power grid reference accident, so the regional grid rated capacity \(S_{\text{BASE}}\) and the maximum load disturbance \(\Delta P_{L_{\text{max}}}\) are 150 MW and 30 MW (0.2 p.u) [5]. To verify that the present method can quickly and effectively prevent frequency deterioration, a 0.2 p.u. step disturbance is set at 1 s, and the duration is 20 s. In this case, the advantages of the present method over Method 1 and Method 2 will be clearly demonstrated. The performance of the frequency deviation and SOC is shown in Table 2 and Figs. 14-15.

Fig. 14 illustrates that all three methods show a better primary frequency control effect than that without energy storage. As analyzed in section II of this article, virtual droop control can effectively reduce \(|\Delta f_{\text{m}}|\) and \(|\Delta f_{\text{s}}|\), but it has no effect on \(\Delta o\). Virtual inertia control has a positive effect on \(|\Delta f_{\text{m}}|\) and \(\Delta o\) but has no effect on \(|\Delta f_{\text{s}}|\). As shown in Fig. 8, Model A is automatically switched under the condition of step disturbance. The output of the BESS in Model A of the degradation stage is shown in (21), which is composed of two parts: droop control output and virtual control output. Among them, the distribution coefficients \(a_1\) and \(a_2\) dynamically adjust the output ratio of the virtual droop part and the virtual inertia part according to the frequency deviation. The outputs of Method 1 and Method 2 in the degradation stage are shown in (35) and (37), respectively. Method 1 is variable coefficient.
droop control, and Method 2 is constant coefficient inertial control. After $|\Delta f_m|$ reaches a maximum value and starts to recover, Model A exits inertia control to prevent inertia control from blocking frequency recovery. That is, in the frequency recovery stage, these three methods all use droop control.

Table 2 shows that $|\Delta f_m|$, $|\Delta f_s|$, $\Delta f_{rms}$ and $\lambda'$ of the present method are the smallest. This means that Model A can stop the deterioration of frequency as fast as possible. $|\Delta f_m|$ and $\lambda'$ of the present method are smaller than that of Method 1 because Model A is dominated by inertia control in the degradation stage, and $|\Delta f_m|$ can be reduced faster than Method 1. At the same time, they are also smaller than that of Method 2 because $a_1$ and $a_2$ of Model A can dynamically adjust the output ratio of the virtual droop part and the virtual inertia part according to the frequency deviation. Compared with the fixed-coefficient inertial control of Method 2, the hybrid control mode of Model A is better for quickly suppressing the frequency deviation. $|\Delta f_m|$ of Method 1 is smaller than that of Method 2 because Method 2 is controlled by $\Delta f_m$. From Fig. 2, it can be seen that $\Delta f_m$ is relatively large only when the frequency begins to change, and $\Delta f_m$ gradually decreases as $|\Delta f_m|$ increases. As shown in (37), the output of Method 2 will be limited; that is, although BESS still has the frequency control capability, it will not continue to contribute to preventing the frequency from deteriorating. Corresponding to the SOC curves of Method 1 and Method 2 in Fig. 15, it can be seen that the SOC of BESS in Method 2 is not fully used. It is worth noting that the SOC index of the present strategy has no advantage compared to the other two methods, as shown in Fig. 15. This is because Model A aims at quickly suppressing frequency deterioration with the highest priority. At this time, energy storage responds to step disturbances with the maximum frequency control capability and does not consider the maintenance and limitation of SOC; therefore, the SOC index is the worst compared to other methods. In addition, $\lambda'$ of the present method is the same speed as Method 1 but slightly faster than Method 2. Since the present method value of $|\Delta f_m|$ is smaller than that of Method 1, the $|\Delta f_s|$ of the present method is still smaller than the value of Method 1.

2) CONDITION 2. LONG-TERM SMALL CONTINUOUS DISTURBANCE

Ten-minute small continuous disturbance data for a province in southern China are shown in Fig. 16. The maximum load disturbance ($\Delta p_{max}$) is 0.02 p.u. As shown in Fig. 8, under
In continuous disturbance conditions, the adaptive strategy in this paper will automatically switch to Model B. In this case, it can be clearly seen that the frequency control output of Method 2 does not have any SOC constraints, and Method 2 is not conducive to the long-term operation of BESS. To make Model B and Method 1 comparable, the two have the same SOC parameter settings. In particular, this article keeps the SOC at 0.5, as in Method 1.

It can be clearly seen from Table 3 that all of the frequency control effect indicators and SOC indicator of the present method are the best. It means that present method is more effective than the other two methods under small continuous disturbance condition. Unlike Method 2, both Method 1 and the present method consider the effect of frequency control on SOC, so the SOC indicator of Method 2 is the worst (Fig. 18). Because the disturbance is constantly changing under the aforementioned conditions, the energy storage system of Method 2 always switches between virtual inertia control and virtual droop control. Meanwhile, a similar load change before and after the switching is not guaranteed. Therefore, Method 2 will increase the system frequency oscillation, as shown in Fig. 17. As shown in (23), Model B gives up frequency control until the SOC is within a reasonable range. If the SOC is reasonable, Model B can participate in frequency control; at the same time, the SOC is restored to 0.5 in the dead zone. Compared with Method 1, the SOC of the present method can be self-healing, so the SOC index of the present method is significantly better than Method 1. In the long run, the present method is more suitable for meeting the frequency control requirements under small continuous load disturbance working conditions. On the one hand, Model B can adjust the frequency deviation caused by small daily disturbances. On the other hand, Model B keeps the SOC of BESS at about 0.5 so that it can respond to step disturbances in different directions (charging or discharging) at any time.

3) CONDITION 3. LOAD DISTURBANCE OF COMBINED STEP AND CONTINUOUS DISTURBANCES
In this case, the simulation time is 600 seconds. The load disturbance shown in Fig. 19 includes a small continuous load disturbance and step disturbance. The present method automatically identifies this type of disturbance. When encountering a frequency jump, Model A is used, and the SOC is not considered for the goal of quickly suppressing the sudden frequency change. Model B can recover and maintain the SOC and control the frequency at the same time. Under this condition, the effectiveness of the proposed method can be more clearly reflected. Fig. 20 and Fig. 21 show the simulation results of the frequency deviation and SOC of the BESS, respectively. The calculation results of the frequency deviation evaluation indices are shown in Table 4.
Table 4 Fig. 20 and Fig. 21 shows that the frequency and SOC indicators of the proposed method are superior to those of the other two methods. The simulation results illustrate that the proposed method can quickly and effectively control the grid frequency. The frequency deviation results shown in Fig. 20 are consistent with the experimental results of the step condition (Fig. 14) and the continuous condition (Fig. 17). The frequency indicator of Method 2 in Table 4 indicates that Method 2 will aggravate the oscillation of the system frequency when encountering different working conditions. At the same time, Fig. 21 shows that Method 2 is not suitable for long-term operation, which is the same conclusion as the continuous disturbance.

It can be seen from Fig. 21 that neither the SOC of present method nor Method 1 has been decreasing as shown in Fig. 15. Compared with condition 1, the step disturbance of condition 3 cuts out of the grid after a period of time. Therefore, the SOC of Method 1 can be stabilized after the disturbance exits the network. Assuming that the system encounters the step disturbance shown in Fig. 19 successively, then Method 1 needs to be continuously discharged, and its SOC will further decrease. Unless it happens to encounter a step disturbance opposite to that in Fig. 19, BESS can absorb energy from the power system, and then the SOC of Method 1 may increase. But, the SOC of present method has not only stabilized but also recovered to 0.5, which can be clearly found from Fig. 18 and Fig. 21.

Present method can automatically identify the change of the disturbance type and switch to the corresponding model to meet the frequency control requirements of different disturbances. Simulation experiment results of condition 3 confirm the analysis of section III that Model A and Model B of the proposed strategy can be switched smoothly and effectively.

In summary, compared with the control method with a variable droop coefficient and considering SOC maintenance (Method 1) and the control method combining inertia control and droop control without considering SOC (Method 2) under three different working conditions, the frequency control performance of the present method was better than that of the other two methods. The control strategy in this paper makes full use of the frequency control capability of...
TABLE 4. A comparison of frequency evaluation indices.

| Indicator | $\Delta f_{0}$/Hz | $\Delta f_{100}$ | SOC_{min} |
|-----------|------------------|------------------|-----------|
| Present Method | -0.01103 | 0.00106 | 0.01349 |
| Method 1 [29] | -0.01403 | 0.00125 | 0.04154 |
| Method 2 [26] | -0.04697 | 0.00218 | 0.4361 |
| Without energy storage | -0.01717 | 0.00151 | / |

BESSs so that they can deal with complex and changeable working conditions and are more suitable for the long-term operation of BESSs.

V. CONCLUSION
In this paper, considering the load disturbance types, we proposed a comprehensive self-adaptive strategy that enables BESS participation in primary frequency control of the power grid. The conclusions are summarized as follows.

(1) The different types of load disturbances in the power system are divided into two categories. Then, the advantages of virtual inertia control and virtual droop control are comprehensively considered. Two control models (termed Model A and Model B) are proposed to match the two load types. In the step disturbance case, the goal of Model A is to quickly suppress the frequency mutation. In the continuous small disturbance case, Model B is switched so that the energy storage can complete SOC recovery while adjusting the frequency.

(2) The proposed adaptive frequency control strategy considering the disturbance type was simulated and verified under three working conditions and compared with other methods. The frequency control performance of the present method was better than that of the other two methods. The results show that the present approach significantly improves the stability of complicated and changeable power systems.

(3) The adaptive control strategy in this paper can improve the renewable energy consumption capacity of the grid. At the same time, it can provide a new reference for BESS economic optimization operations and long-term planning.

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