Power Configuration Scheme for Battery Energy Storage Systems Considering the Renewable Energy Penetration Level

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With the increase of the renewable energy penetration (REP) level in the interconnected power grid, the proportion of the grid-connected conventional synchronous generators reduces continuously, resulting in the decrease of the system inertia. The insufficient system inertia brings challenges to the system frequency stability. Battery energy storage systems (BESSs), regarded as the high-quality frequency regulation resource, play an important role in maintaining the frequency stability of the system with the high REP level. To configure the proper power of BESSs in system frequency regulation, a BESS power configuration scheme (PCS) considering the REP constraint is proposed in this paper. In particular, the process to obtain the REP boundary of the interconnected grid on the premise of system frequency stability is included in the PCS, and the optimal power configuration of the BESS is further determined on the analysis of the BESS impact on the REP boundary. Furthermore, a simulation model of the Australian five-area interconnected power grid is built in MATLAB/Simulink, and the proposed REP-constrained PCS is verified and analyzed. At last, the promising results show that the PCS can take full advantages of the BESS in frequency regulation and meet the system requirement of the frequency stability at a particular REP level.

Keywords: renewable energy penetration, battery energy storage system, interconnected power grid, system frequency stability, system inertia

INTRODUCTION

To reduce the greenhouse gas emission, replacing fossil energy generation by renewable energy generation (REG) has become an inevitable trend in the modern power grid. At the end of 2020, the capacity of the grid-connected REG including photovoltaic and wind generation reached 1300 GW, accounting for 9.4% of the total installed power generation capacity (Khan et al., 2021) all over the world. Unlike the conventional generators, REG connected to the power grid via power electronic converters cannot provide the system inertia and the frequency regulation support when a load disturbance occurs (De Carne et al., 2020). Meanwhile, the output of REG has high fluctuation and intermittency, which requires more active power reserves to maintain the system frequency stability. Also, the frequency stability issue becomes worse (Ortiz-Villalba et al., 2020; He et al., 2020), when REG is absorbed across control areas via the transmission lines in the interconnected power grid. Therefore, with the increase of the renewable energy penetration (REP) level, the frequency
The equivalent dynamic model of the control area as shown in Figure 1 consists of several generators and BESSs. The model of
the BESS can be equivalent to a first-order inertia block, according to Ramalingam et al. (2018) and Calero et al. (2021), and the conventional generator is constructed referring to Liang et al. (2018). Also, the frequency deviations $\Delta f$ caused by the system load fluctuations can be stabilized dynamically by the inertial response and frequency regulation from generators and BESSs. As a part of frequency regulation, the droop coefficients of Thermal Gen, Hydro Gen, and BESSs are denoted $R_{tg}$, $R_{hg}$, and $R_B$, respectively. Particularly, the participation of the BESS in frequency regulation is indicated by the configuration factor $\alpha$, which can be deduced by the BESS PCS. In addition, $P_{AGC}$ denotes the automatic generation control signal, $M$ and $D$ are the inertial constant and damping coefficient, and $\Delta P_L$ denotes the net load power fluctuations. $\Delta P_{tg}$, $\Delta P_{hg}$, and $P_B$ denote the output power of Thermal Gen, Hydro Gen, and BESSs for frequency regulation. Note that $P_B$ in Figure 1 is under
constrains of the optimal power configuration for the BESS. More details of the control area model are shown below.

**Dynamic Model of the Conventional Generators**

The principles of Thermal Gen and Hydro Gen in frequency regulation are similar, but the dynamic models of those two Gens are different because of the different mechanical structures. The simplified dynamic model of Thermal Gen is shown in Figure 2A (Zhang et al., 2017), which consists of a governor and a steam turbine. In detail, the dynamic model of the governor consists of three parts: the frequency regulation dead zone, the droop coefficient, and the response delay, while the output is the opening change $\Delta Y$ representing the steam valve of the steam turbine. The governor of Thermal Gen can determine whether the generator participates in frequency regulation by measuring the system frequency deviations, as long as $\Delta f$ cross the frequency dead band. Also, the governor can determine the adjustment degree of the control valve by setting the droop coefficient $R_{tg}$ and the primary frequency regulation range according to the droop characteristics of the generator. The response delay of the governor is simulated as a first-order inertia model, and $T_{tg}$ is the time constant of the governor. Meanwhile, in the model of the steam turbine, $T_{ch}$, $T_{th}$, and $T_{hp}$ are the adjustment response time, the time constant, and the gain coefficient of the re heater, respectively. Finally, the output value of the frequency regulation power $\Delta P_{tg}$ is obtained considering the operating boundary of the governor.

Similarly, the dynamic model of Hydro Gen is composed of the governor and the hydro turbine, as shown in Figure 2B. Specifically, the governor consists of the frequency regulation dead zone, the droop coefficient, and the response delay. Referring to Alhejaj and Gonzalez-Longatt (2017), the transient parameters $T_r$ and $R_l$ are used to simulate the reverse variation of the mechanical power caused by the mechanical inertia of water. Also, $T_w$ represents the required time for the water accelerating from standstill to velocity $V_o$ in the hydro turbine model. At last, according to the above analysis, the transfer functions $G_{tg}$ and $G_{hg}$ of Thermal Gen and Hydro Gen can be derived as follows:

$$G_{tg}(s) = \frac{\Delta P_{tg}(s)}{\Delta f(s)} = -\frac{1 + sP_{tg}T_{rh}}{R_{tg}(1 + sT_{tg})(1 + sT_{ch})(1 + sT_{th})},$$

(1)

$$G_{hg}(s) = \frac{\Delta P_{hg}(s)}{\Delta f(s)} = -\frac{(1 + sT_r)(1 - sT_w)}{R_{tg}(1 + sT_{hp})(1 + sT_{ch}(R_l + R_r))(1 + 0.5sT_w)},$$

(2)

**Dynamic Model of BESS**

To represent the external characteristics of the BESS participating in the load frequency control, the dynamic model of the BESS can be expressed as a first-order inertial control block in Figure 2C. In the model, $T_p$ is the time constant used to describe the response time delay of the BESS (Kundur et al., 1994). Meanwhile, the droop coefficient $1/R_p$ represents the proportional relationship between the BESS frequency regulation power and the system frequency deviations. Also, the blocks describing the BESS charging and discharging power range and BESS capacity boundaries are added. At last, the transfer function of BESS $G_B$ is shown as

$$G_B(s) = \frac{P_B(s)}{\Delta f(s)} = -\frac{1}{R_p(1 + sT_p)}$$

(3)

**OPERATION OF THE PENETRATION LEVEL–CONSTRAINED PCS FOR BESS**

The REP level–constrained PCS can dynamically determine the BESS frequency regulation power configuration coefficient $\alpha$, based on the REP level the power system is required to absorb and the frequency stability requirements. And the PCS can further realize the power configuration of the BESS participating in system frequency regulation. The process of the REP level–constrained PCS is shown in Figure 3. In general, the PCS for the BESS includes the system REP level calculation (RLC) block and BESS power configuration (BPC) block. More details about the proposed PCS are introduced below.

**REP Level Calculation Block**

In the interconnected power grid, the power mismatch between the generation and the load leads to the system frequency deviations, which is the key index of the system stability. The traditional generators can stop the frequency drop ($\Delta f_{min}$) and stabilize the frequency around the nominal value (50 or 60 Hz) after a short while, through their own inertia control and the frequency regulation control. To meet the severe active power imbalance of the power system, the under/overload-shedding mechanisms are triggered to maintain the system frequency stability.

Primarily, the conventional generators contribute to the system inertia, as their rotational speed is synchronous to the system frequency. Also, the relationship between the mechanical power, the electrical power, and the rotation speed of the synchronous generator is shown in Eq. 4. The expression of the system inertia is shown in Eqs 5, 6, which is a function of $\omega_r$. The change of the generator’s electric output power $\Delta P_g$ caused by the system load fluctuation is shown in Eq. 7. Also, the change of $\Delta P_g$ further results in the shift of the generator speed, which further causes the frequency fluctuation of the control area. Furthermore, the influence of load fluctuations and system inertia on the system frequency deviations can be deduced in Eq. 8 from Eqs 4, 7. In summary, the synchronous generator can effectively smooth the system frequency drop ($\Delta f_{min}$) due to the rotational inertia generated by its own mechanical structure:

$$\Delta P(s) = \Delta P_g(s) - \Delta P_e(s) = M\Delta \omega(s),$$

(4)

$$M = 2H,$$  

(5)

$$H = \frac{j\omega_r}{P_G},$$

(6)
\[ \Delta P_E(s) = \Delta P_L(s) + \Delta P_{lf}(s) = \Delta P_L(s) + D\Delta \omega(s), \quad (7) \]

\[ \Delta \omega(s) = \frac{1}{DP_L(s) - DP_L(s)} = \frac{1}{D + sM}, \quad (8) \]

\[ \Delta P_C(s) = \Delta P_{tg}(s) + \Delta P_{hg}(s), \quad (9) \]

where \( \Delta P_C \) is the mechanical power change of the conventional generators and the corresponding \( \Delta P_E \) is the electromagnetic power; \( \Delta P_{tg}(s) \) and \( \Delta P_{hg}(s) \) are the output values of frequency regulation power of Thermal Gen and Hydro Gen, respectively; \( M \) is the sum of generator inertia constants in the control area; \( \Delta \omega \) is the angular frequency deviation of the generator; \( DP_L \) is the load fluctuation; \( \Delta P_{lf}(s) \) is the frequency-sensitive load change; and \( D \) is the system load damping constant.

Unlike the conventional generator, renewable energy generation is unable to participate in frequency regulation because renewable energy generation does not have the rotational inertia and usually operates on its maximum power point. Meanwhile, with the increase of the REP level, the proportion of the traditional generators decreases. In other words, a downward trend in the overall inertia level of the power system leads to the insufficient frequency regulation capabilities and the instability of the system frequency. Therefore, the interconnected power grid has a limitation of REP.

The RLC block is used to calculate the REP boundary that the interconnected grid can withstand under the premise of system frequency stability. As shown in Figure 3, the PLC block sets the load condition in advance according to the power system parameters and introduces a large load disturbance to test the frequency stability. To observe the REP boundary, a series of tests about whether the system frequency deviations exceed the limitation under the same load disturbance event are applied by increasing the REP level step by step. Thus, the maximum REP level in a certain load condition is obtained. Furthermore, several typical load conditions are introduced one by one, and the maximum REP level of each load condition is determined. At last, the minimum REP level of the interconnected power grid is obtained by comparing the maximum REP levels in different load conditions.

**BESS Power Configuration**

A virtual droop control strategy is usually adopted for the BESS in the primary frequency regulation. In other words, the BESS can imitate the droop characteristic of the generator in response to the system frequency deviation. The dynamic model of the BESS.
including the virtual droop control strategy is introduced in Figure 2C. For the same frequency deviation, the power from the BESS \( P_B \) can be adjusted by the BESS power configuration coefficient \( \alpha \), and the influence of BESS on the frequency stability can be deduced in Eq. 10. Furthermore, the system amplitude–frequency characteristic functions can be written in Eqs 11, 12, respectively, representing the system with and without BESS. The corresponding amplitude–frequency characteristic curves are shown in Figure 4. In detail, the amplitudes are very small or relatively close when the frequency deviations are caused by the low-frequency or high-frequency load fluctuations, no matter whether BESSs are involved. However, the amplitude of \( H_{Bg}(s) \) is obviously smaller than that of \( H_{tg}(s) \) when the middle-frequency load fluctuations occur. Also, a larger \( \alpha \) leads to a smaller amplitude of \( H_{Bg}(s) \). Therefore, the frequency deviation suppression effect brought by load fluctuations in the middle-frequency band is stronger, with the increase of the configuration coefficient \( \alpha \):

\[
\Delta f(s) = \frac{\Delta P_g(s) + \Delta P_{bg}(s) + P_B(s) - \Delta P_L(s)}{D+sM} = \frac{-\Delta P_L(s)}{D+sM - G_{tg} - G_{tg} - \alpha G_B},
\]

(10)

\[
H_{Bg}(s) = \frac{\Delta f(s)}{\Delta P_{tg}(s)} = \frac{1}{D+sM - G_{tg} - G_{bg} - \alpha G_B},
\]

(11)

\[
H_{tg}(s) = \frac{\Delta f(s)}{\Delta P_L(s)} = \frac{1}{D+sM - G_{tg} - G_{tg}}.
\]

(12)

Based on the above theoretical analysis, the BESS participating in the primary frequency regulation can improve the ability of the power system to cope with the load deviations effectively. In this way, the aim of the REP level of the interconnected power grid can be guaranteed, and the system frequency deviation can always meet the system stability requirement when the load disturbance occurs under a certain configuration coefficient \( \alpha \). Thus, the optimal power configuration of the BESS can be deduced according to the configuration coefficient \( \alpha \).

The BPC block is used to calculate the minimum BESS charge and discharge power that can enable the control area to meet the aim of the REP level and frequency stability. As shown in Figure 3, the necessity of involving the BESS in frequency regulation is determined in the first place, by comparing whether the maximum REP levels are larger than the aim of the REP level of the control area. The BESS power configuration coefficient \( \alpha \) is gradually increased, when the aim of the REP level cannot be met. A series of tests are applied until the system frequency stability of the control area with the target REP level is satisfied. Finally, according to the proper power configuration coefficient \( \alpha \), the optimal BESS power configuration that meets the frequency stability of the region is obtained.

**SIMULATION AND DISCUSSION**

The Australian power grid is regarded as one of the longest interconnected power grids, as shown in Figure 5, and can be generally simplified as a 5-area 14-bus system. The maximum power generation capacity of the system is 25,430 MW, while the maximum load demand is 24,800 MW. According to the Australian state layout, Area #2 (New South Wales) and Area #3 (Victoria) are typical load centers and Area #4 (Queensland) and Area #5 (South Australia) are rich in solar energy and wind energy resources, respectively. Thus, the feasibility of the REP level–constrained PCS for the BESS is verified based on the Australian power grid, as it is a typical interconnected power grid with high REP.

The dynamic model of the Australian interconnected power grid in MATLAB/Simulink is shown in Figure 6 based on the system data (Gibbard and Vowles, 2010) in Table 1, including the traditional generators, renewable generators, and BESSs in each area. To consider the actual operation of the Australian power grid, five typical load scenarios (Gibbard and Vowles, 2010) are formulated in Table 2, which are the peak scenario, heavy scenario, medium heavy scenario, medium scenario, and light scenario. Furthermore, a positive \( P_{12} \) means the active power flows from Area #4 to Area #2, and the negative one means the opposite power flow. \( P_{27}, P_{19}, \) and \( P_{55} \) follow the same rules. In addition, Area #2 and Area #4 are chosen as examples to configure the BESS verifying the influence of BESS on system frequency control in the load center and the renewable generation center.

**Feasibility of RLC Block**

Based on the former theoretical analysis, the inertia of the control area decreases with the increase of the REP level, which results in the system frequency instability. In the simulation, a fixed step load disturbance of ±5% p.u. occurred in the control area, and none of frequency deviations exceeding ±0.25 Hz is defined as the system frequency stability. Also, the frequency recovery time is neglected as the indication of the system frequency stability because the response time of the BESS is faster than that of the traditional generators. The REP boundary of the control area is calculated by increasing the REP level of Area #2 and Area #4 from 0 gradually, until the constraint of frequency stability is no longer satisfied. In the heavy load scenario, the frequency deviations of the load center Area #2 and the renewable generation center Area #4 are shown in Figures 7A,B, while the performance of the frequency fluctuations is indicated in Tables 3, 4.
In detail, the system frequency of the load center Area #2 becomes unstable when the REP level reaches 5%, and the REP boundary of the area is 5%. Similarly, the renewable generation center Area #4 has an REP boundary of 9%. Thus, with the decrease of the system inertia, $\Delta f_{\text{nadir}}$ continues to approach the system stability limit $\pm 0.25$ Hz. Also, the rate of change of frequency and the time to achieve the frequency recovery increase.

**FIGURE 5** | Australian 5-area 14-bus power grid.
Specifically, Area #4 and Area #2 are regarded as the renewable generation center and the load center, respectively, and the grid-connected traditional generators in the heavy load scenario provide more system inertia in the renewable generation center Area #4. Meanwhile, Area #2 transfers more power to the load center through the tie line, and part of the renewables is absorbed actually in the load center Area #2. Thus, the boundary of the REP level of the renewable generation center Area #4 is higher than that of the load center Area #2.

Furthermore, as the REP level of the load center is set to 5%, Area #2 can meet the requirements of frequency stability in the heavy load scenario. Another four load scenarios from Table 2 are tested, and the frequency fluctuations are shown in Figure 8A. The maximum Δ\text{P}_{\text{nadir}} of Area #2 does not exceed ±0.25 Hz in
heavy and medium load scenarios but goes across the limitation in peak, medium heavy, and light scenarios. Similarly, considering the REP level of the renewable generation center Area #4 as 9%, the simulation results of five different load scenarios are shown in Figure 8B. Similar simulation results are obtained such that the REP boundary of a control area changes according to the load scenarios.

At last, considering the comprehensive effectiveness of the system inertia and load scenarios on the system frequency stability, the REP boundaries of five control areas are shown in Table 5, according to the calculation process of the RLC block. Obviously, the REP level cannot be satisfied in both load centers and renewable generation centers, and it is necessary to configure the BESS to improve the REP level.
Performance of BPC Block
Based on the former theoretical analysis, BESSs have high control accuracy and fast response speed, which can improve the system frequency stability by mitigating the frequency deviation quickly. To verify the effectiveness of the BPC block, optimal BESS power is configured in both the load center and the renewable energy generation center.

The target of the REP levels of load centers and renewable generation centers is set to 5 and 10%, respectively. According to the results in Table 3, the smallest REP levels of Area #2 and Area #4 occur under the medium heavy load scenario. Thus, to achieve the setting REP level, BPC block calculation is applied by increasing the configuration coefficient $\alpha$ gradually, and the simulation results of the frequency fluctuations are shown in Figures 9A,B.

In particular, the maximum $\Delta f_{\text{nadir}}$ of Area #2 and Area #4 exceeds the frequency limitation, if BESSs are not equipped in areas. Meanwhile, the maximum $\Delta f_{\text{nadir}}$ decreases gradually and reaches within $\pm 0.25$ Hz eventually with the increase of BESS configuration coefficients. The system frequency fluctuations are mitigated in a shorter period. Thus, the performance of system frequency regulation improves significantly with BESS involvement. Finally, the configuration parameters of BESSs are obtained based on the target REP levels, and the results are shown in Table 6. To sum up, the target REP levels are achieved by the proposed PCS for the BESS.

CONCLUSION
This paper proposes a BESS PCS considering the REP constraint on the premise of system frequency stability. At the beginning, the dynamic models of Thermal Gen, Hydro Gen, and BESSs are established. The REP-constrained PCS can dynamically determine the BESS power configuration by comparing the target REP levels and the REP boundaries of each control area in different load scenarios. A model of the Australian five-area interconnected power grid is established in
MATLAB/Simulink to verify the effectiveness of the PCS, and the suggested BESS power for each control area is obtained. Therefore, high REP level can be achieved in the future, as the BESS mitigates the system frequency fluctuations effectively, and the proposed PCS indicates the optimal BESS power. In addition, the implementation of the BESS is not only for frequency regulation but also for the way to configure BESS power in multiple purposes, which will be discussed in further work.

DATA AVAILABILITY STATEMENT
The original contributions presented in the study are included in the article/supplementary material, and further inquiries can be directed to the corresponding author.

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AUTHOR CONTRIBUTIONS
QC proposed the concept of the project, and FW acted as the project administrator. YC and HL designed the system model and established the details of the power configuration scheme. ZS and BL analyzed the data and carried out the simulation. RX and SZ contributed to funding acquisition and writing the paper. All authors approved the submitted version.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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NOMENCLATURE

ACE Area control error
B Secondary frequency regulation coefficient
BESS Battery energy storage system
BPC BESS power configuration
D Load damping coefficient
Fhp Gain coefficient of the reheater
$\Delta f_{\text{nadir}}$ Frequency drop
G Governor constant
GB Transfer function of the BESS
Ghg Transfer functions of Hydro Gen
Gtg Transfer functions of Thermal Gen
H Inertia constant of the synchronous generator
HB(s) Amplitude–frequency characteristic function with the BESS
HG(s) Amplitude–frequency characteristic function without BESS
M Generator inertia constant
PAGC Automatic generation control signal
PCS Power configuration scheme
R Speed regulation constant
RB Droop coefficients of the BESS
REG Renewable energy generation
REP Renewable energy penetration
Rhg Droop coefficients of Hydro Gen
RLC REP level calculation
Rt Transient parameters used to simulate the reverse variation of the mechanical power

$\text{Rtg}$ Droop coefficients of Thermal Gen
$\text{TB}$ Time constant used to describe the response time delay of the BESS
$\text{Tch}$ Adjustment response time of the reheater
$\text{Thg}$ Time constant of the hydro governor
$\text{Ti}$ Synchronizing torque coefficient between adjacent areas
$\text{Tr}$ Transient parameters used to simulate the mechanical inertia of water
$\text{Trh}$ Time constant of the reheater
$\text{Ttg}$ Time constant of the thermal governor
$\text{Tw}$ Required time for the water accelerating from standstill to velocity $V_0$ in the hydro turbine model
$\text{V}$ Voltage magnitude
$\alpha$ Energy storage configuration factor
$\Delta f$ Frequency deviations
$\Delta f_i$ Frequency deviations in the $i$th adjacent area
$\text{PB}$ Output value of the frequency regulation power of the BESS
$\Delta \text{PE}$ Electrical power variation of the generator set
$\Delta \text{PG}$ Mechanical power variation of the generator set
$\Delta \text{Phg}$ Output value of the frequency regulation power of Hydro Gen
$\Delta \text{PL}$ Net load power fluctuations
$\Delta \text{PL}(s)$ Frequency-sensitive load change
$\Delta \text{Ptg}$ Output value of the frequency regulation power of Thermal Gen
$\Delta \text{Ptie}$ Power exchanged from other areas through the tie lines
$\Delta Y$ Opening variation of the steam valve of the steam turbine
$\Delta \omega$ Generator angular frequency deviation
$\omega$ Generator rotor speed