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Cooperative Frequency Regulation for Thermal Power and Energy Storage Clusters via Hierarchical SOC Control

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***Abstract*—Distributed energy storage is crucial for frequency stability in low-inertia grids. However, conventional lumped models mask unit heterogeneity, causing premature depletion of low-state of charge (SOC) units known as the "barrel principle". To address this, a hierarchical cooperative control strategy for thermal energy storage systems (thermal power and energy storage) prioritizing SOC consistency is proposed. A discrete-time state-space model is constructed to capture heterogeneous dynamics. The proposed two-layer architecture features an upper layer discrete filter for spectral-based power allocation and a lower layer adaptive consistency algorithm. A non-linear power-exponent weighting mechanism dynamically recalibrates output weights based on real-time SOC deviations. The simulation results demonstrate that the strategy effectively suppresses frequency fluctuations and ensures rapid SOC convergence. By preventing overcharge or overdischarge of the individual unit, the approach significantly enhances the effective capacity and operational robustness of the joint system.**

***Index Terms*—Distributed energy storage system; Frequency regulation; Hierarchical control.**

I. INTRODUCTION

Driven by global decarbonization targets [1]–[3], rapid integration of renewables has significantly reduced system inertia, challenging frequency stability. Since traditional thermal units are constrained by slow ramping, integrating fast-responding battery energy storage systems (BESS) has become a consensus solution. However, the existing literature often models storage systems as lumped entities, overlooking internal variations. For example, Zheng, Wei, Xu, and Chen [4] employ a water-filling algorithm based on total capacity, effectively assuming uniform operating conditions. In practice, parameter heterogeneity (e.g., state of charge (SOC) differences) among units is unavoidable. This renders simple equal distribution strategies ineffective, causing the "barrel principle", where specific units suffer overcharge or overdischarge. Consequently, this phenomenon severely constrains overall efficacy of the cluster's regulation and operational lifespan.

To address these challenges, this paper proposes a distributed cooperative frequency regulation strategy underpinned by a hierarchical architecture. In contrast to traditional centralized control methods, which often suffer from the "curse of dimensionality" and computational latency when processing high-dimensional variables, this study adopts a lightweight, nonlinear adaptive algorithm. This mechanism establishes a strong coupling between frequency regulation and state balancing. By dynamically recalibrating power weights according to real-time SOC deviations, the proposed strategy achieves the simultaneous convergence of frequency support and internal state consistency. The simulation results demonstrate that the strategy not only exhibits superior dynamic response performance but also significantly suppresses state mismatches within the cluster, enhancing the system's adaptability to complex operating conditions.

The heterogeneity among distributed energy storage units originates from multiple practical factors, including manufacturing tolerances, uneven aging due to disparate operational histories and thermal conditions, and staggered commissioning times. These inherent disparities lead to significant variations in rated capacity, initial SOC, and state of health (SOH) across units within the same cluster. In conventional frequency regulation strategies that ignore such heterogeneity, the power commands are often distributed uniformly or based solely on rated power, which inevitably causes some units to become overcharged or overdischarged prematurely. This not only reduces the effective usable capacity of the entire cluster, as dictated by the "barrel principle", but also accelerates the degradation of the most stressed units due to a deeper depth of discharge and increased thermal stress. Consequently, accelerated aging further widens the parameter disparities, creating a vicious cycle that undermines both the short-term frequency support capability and the long-term economic viability of the energy storage system.

Furthermore, the "barrel principle" not only curtails the duration of the regulatory process, but also induces accelerated aging in the overutilized units due to deeper discharge cycles and increased thermal stress. This heterogeneous degradation further exacerbates parameter disparities, creating a vicious cycle that undermines the long-term economic viability and reliability of the BESS cluster. Existing distributed control strategies, often relying on linear

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consensus protocols, struggle to achieve rapid state balancing while simultaneously executing precise power dispatch for frequency regulation. There is a discernible gap for a control framework that tightly couples these two objectives within a computationally efficient architecture. This paper aims to bridge this gap by proposing a hierarchical control strategy that embeds a non-linear, state-aware weighting mechanism within a discrete-time "fast-slow" separation framework.

II. SYSTEM MODEL CONSTRUCTION

To deeply investigate the consistency issues within distributed storage clusters while avoiding the computational redundancy of high-order differential equations in long-term simulations, this paper constructs a system frequency response model based on discrete-time state space. This model mainly includes the regional grid frequency dynamic model and the heterogeneous energy storage cluster model.

A. Discrete-Time Model of Regional Grid Frequency Dynamics

Traditional power system frequency response analysis is usually based on the rotor motion equation. Considering that primary frequency regulation focuses on the dynamic relationship between active power and frequency and that the time scale is in the range of seconds to minutes, this paper makes the following reasonable assumptions:

1. Ignore the influence of network topology and reactive voltage, equating the regional grid to a single-machine load system;
2. Assume that system load fluctuation is an exogenous disturbance variable. Based on these assumptions, the first-order differential equation of system frequency can be expressed as [5]

$$2H\frac{df(t)}{dt} = P_G(t) + P_{ESS}(t) - P_L(t) - D\times\Delta f(t), \qquad (1)$$

where H is the system equivalent inertia constant, representing the system's ability to resist frequency changes, D is the load damping coefficient, and P_G, P_{ESS}, and P_L are the thermal unit output, total energy storage system output, and load disturbance, respectively.

Since modern wide area measurement systems and digital controllers operate based on discrete sampling, to facilitate the implementation of digital control strategies and numerical simulation, this paper uses Euler's method to discretize the above equation. Assuming the system sampling step is T_s, the frequency state transition equation from moment k to $k + 1$ can be derived as [6]

$$\Delta f(k+1) = \Delta f(k) + \\ +\frac{T_s}{2H}\left[P_G(k) + \sum_{i=1}^{N} P_{bat,i}(k) - P_L(k) - D\times\Delta f(k)\right]. \qquad (2)$$

Compared to the continuous domain model, this discrete model has significant advantages: first, high computational efficiency, capable of rapidly processing long-time-scale continuous disturbance simulations; second, strong compatibility, capable of directly mapping the actual operation logic of digital controllers (i.e., calculating the control command for $k + 1$ based on the sampled value at the current moment k).

B. Distributed Heterogeneous Energy Storage Cluster Model

Existing studies often use a single equivalent model to represent energy storage power stations, assuming that all battery units have consistent parameters. However, in practical engineering, storage stations are often composed of a large number of dispersed battery clusters connected in parallel. Influenced by production batches, commissioning times, and ambient temperatures, there is significant heterogeneity in the rated capacity and initial SOC of each unit. Ignoring this difference leads to distorted simulation results that fail to reflect the "barrel effect" (short-board effect) in actual operation.

Therefore, this paper constructs a storage cluster model containing N parallel units. The dynamic change of the SOC for the i^{th} storage unit is actually the integral of active power over the time dimension. In the discrete domain, its state update equation is described as [7]

$$SOC_i(k+1) = SOC_i(k) - \frac{\eta\times P_{bat,i}(k)\times T_s}{E_{rated,i}}, \qquad (3)$$

where $E_{rated,i}$ is the rated capacity of the i^{th} unit, reflecting the capacity heterogeneity of the cluster; η is the comprehensive charging/discharging efficiency.

To ensure that the model conforms to physical reality, strict operational constraints must be introduced:

$$\begin{cases} |P_{bat,i}(k)| \le P_{max,i}, \\ SOC_{min} \le SOC_i(k) \le SOC_{max}. \end{cases} \qquad (4)$$

By constructing the above matrix model containing N-dimensional state variables, this paper can precisely track the independent trajectory of each battery unit in the simulation, providing a precise mathematical foundation for the subsequent verification of the consistency control strategy.

The heterogeneity encapsulated in the rated energy capacity of the i^{th} energy storage unit (E_i) and initial SOC is not static. It originates from several practical factors:

1. Manufacturing tolerances leading to slight capacity variations even within the same batch;
2. Non-uniform aging (state of health (SOH), SOH divergence) caused by differing operational histories and temperature gradients across the installation site;
3. Commissioning time lags resulting in different initial charging states. The discrete-time state-space model formulated in (2) and (3) explicitly captures these individual dynamics, enabling a granular analysis that a lumped model fundamentally cannot provide. This fidelity is crucial to accurately simulating the state divergence problem and validating the proposed consistency controller.

C. Assumptions and Practical Implications

The discrete-time model developed in this paper relies on four key assumptions that balance tractability with physical fidelity. The regional grid is simplified as a single-machine equivalent, which is adequate for active power-frequency studies on the seconds-to-minutes time scale but neglects inter-area oscillations and voltage dynamics. Load fluctuations are treated as exogenous disturbances, a standard practice for evaluating controller robustness, yet real-world renewables introduce correlated variability. Thermal units are represented by a first-order low-pass filter that captures their dominant ramping limitation, omitting detailed boiler turbine dynamics that are less relevant for the slow component assigned to them. Energy storage units are modeled solely by SOC update equations with constant efficiency, ignoring BMS-imposed power limits, thermal effects, and SOH degradation. These simplifications are deliberately chosen to isolate and validate the proposed hierarchical SOC-adaptive control; relaxing them in future work will further confirm the practicality of the strategy under more realistic conditions.

These assumptions are deliberately chosen to isolate the core contribution, hierarchical SOC-adaptive control, and to keep the model compatible with discrete-time digital controllers. The simulation results in Section IV demonstrate that even under these simplifications, the proposed strategy effectively suppresses frequency deviations and eliminates SOC disparities. Future extensions will relax some of these idealizations to further validate the approach under more realistic conditions, including communication imperfections and multi-area networks.

III. Hierarchical Cooperative Control Strategy for Thermal Power and Energy Storage Clusters

Addressing the two control objectives of “system-level power allocation” and “device-level state balancing” on different time scales in the thermal power and energy storage joint frequency regulation system, this paper proposes a two-layer cooperative control architecture. The upper layer controller is based on the principle of spectrum analysis, utilizing a discrete filter to achieve complementary power allocation between thermal power and the storage cluster; the lower layer controller introduces a non-linear adaptive weight function to dynamically restructure power within the storage cluster to achieve SOC consistency convergence.

A. Upper Layer Strategy

At the instant when the system is subjected to a load disturbance, the total frequency regulation power demand $P_{req}(k)$ is generated by droop control based on the real-time frequency deviation. To fully utilize the regulation characteristics of different resources, the upper layer strategy aims to achieve “fast-slow separation”:

1. Thermal Units (slow dynamic resource): Constrained by mechanical inertia, boiler ramp rates, and wear costs, thermal units are not suitable for responding to severe high-frequency fluctuations. This paper designs a first-order low-pass filter to extract the low-frequency smooth component of the regulation demand as the thermal power command. In the discrete domain, its output $P_G^{ref}(k)$ update law is [8]

$$P_G^{ref}(k) = (1-\alpha)\times P_G^{ref}(k-1) + \alpha \times P_{req}(k), \tag{5}$$

where $\alpha = T_s/(T_g + T_s)$is the filter coefficient, and T_g is the time constant of the thermal unit. This algorithm ensures a smooth transition of thermal output, avoiding mechanical wear.

2. Energy Storage Cluster (fast dynamic resource): Utilizing the millisecond-level response characteristics of energy storage, it undertakes the high-frequency components filtered out by thermal power and the instantaneous power deficit

$$P_{ESS}^{total}(k) = P_{req}(k) - P_G^{ref}(k). \tag{6}$$

This link ensures the total power balance of the system and achieves orthogonal complementarity between thermal power and energy storage on the time scale.

B. Lower Layer Strategy

The core task of the lower layer control is to reasonably allocate the total demand $P_{ESS}^{total}(k)$ to N heterogeneous battery units. Traditional average allocation strategies ignore single-unit SOC differences, easily triggering the “barrel effect”. Therefore, this paper constructs an adaptive weight function based on the perception of the SOC state. Define the consistency weight factor $\lambda_i(k)$ for the i^{th} storage unit at moment k. To strengthen the intensity of the regulation when the SOC deviation is large, a non-linear power function is introduced to build the mapping relationship as follows.

Scenario 1: Cooperative Discharging Mode ($P_{ESS}^{total} > 0$)

When the system frequency drops and storage support is needed, units with higher SOC should undertake more output. The weight function is designed as [9]

$$\lambda_i(k) = \left(SOC_i(k)\right)^{\beta}, \tag{7}$$

where $\beta(\beta > 1)$is the consistency adjustment factor. A larger β results in a more significant amplification effect on the output of high-SOC units, forcing them to release energy quickly to catch up with the average level.

Scenario 2: Cooperative Charging Mode ($P_{ESS}^{total} < 0$)

When the system frequency overshoots and storage needs to absorb power, units with lower SOC should prioritize charging. The weight function is designed as

$$\lambda_i(k) = \left(1 - SOC_i(k)\right)^{\beta}. \tag{8}$$

Based on the above weights, the final power command $P_{bat,i}^{ref}(k)$ for the i^{th} unit is obtained through normalization calculation

$$P_{bat,i}^{ref}(k) = P_{ESS}^{total}(k) \times \frac{C_i \times \lambda_i(k)}{\sum_{j=1}^{N} C_j \times \lambda_j(k)}, \tag{9}$$

where C_i is the capacity correction coefficient (if the rated capacity of each unit is the same, then $C_i = 1$). This allocation mechanism strictly ensures that the total output of the cluster tracks the upper layer command.

C. Analysis of Consistency Convergence Mechanism

The essence of the proposed strategy to achieve SOC consistency lies in the construction of a negative feedback mechanism with respect to SOC deviation.

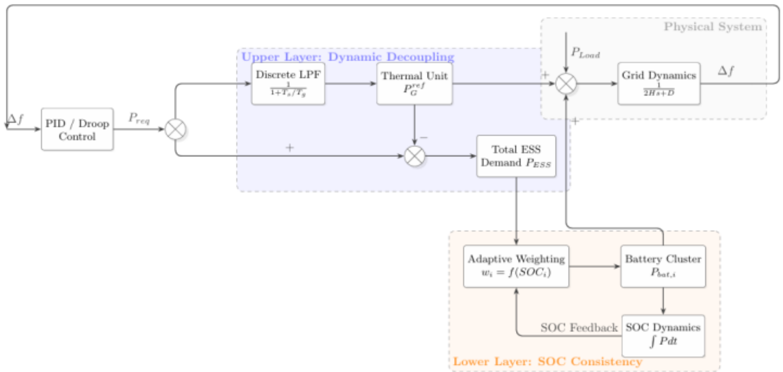

Fig. 1. Hierarchical cooperative control strategy for thermal power and energy storage clusters.

Taking the discharging process as an example, assume that the SOC of unit i(SOC_i) is higher than the cluster average SOC_{avg}. Since the power function $\beta > 1$ is introduced, its allocation weight λ_i will be significantly greater than the linear proportion, causing the discharge rate $dSOC_i/dt$ of this unit to be much faster than that of other units [10]. Mathematically, this is equivalent to making the time derivative of the standard deviation of the SOC distribution (σ_{SOC}) constantly less than zero

$$\frac{d(\sigma_{SOC})}{dt} < 0. \tag{10}$$

This implies that as the frequency regulation process continues, regardless of how discrete the initial states are, the SOC trajectories of all units will inevitably converge to the same horizontal level. This maximizes the available capacity of the storage cluster and avoids unplanned system outages caused by single-unit overdischarge. The control strategy block diagram is shown in Fig. 1.

IV. CASE DISCUSSION

To verify the effectiveness of the proposed hierarchical cooperative control strategy, a simulation model of a thermal power and energy storage joint frequency regulation system containing five heterogeneous distributed energy storage units was built on the MATLAB platform.

The simulation parameters are set as follows: system reference frequency 50 Hz, equivalent inertia constant H = 5 s, and thermal unit rated power 100 MW. The storage cluster contains five units, with an initial SOC set at [0.90, 0.75, 0.60, 0.40, 0.20], respectively, to simulate an extreme unbalanced state. The consistency adjustment factor is set to β= 3.5. The sampling interval is set to T_s = 0.01 s, which is consistent with typical wide area measurement systems (100 Hz) and ensures adequate resolution to capture electromechanical transients while maintaining computational efficiency. The thermal unit time constant T_g = 5 s is chosen to reflect the dominant ramping characteristic of conventional coal-fired generators in primary frequency regulation. The consistency adjustment factor β = 3.5 is determined through multiple pre-simulations: a higher β accelerates SOC convergence but may cause transient power spikes, while a lower β smoothens allocation yet prolongs balancing time. The selected value offers a favorable trade-off between convergence speed and power smoothness under the tested scenarios.

Although five storage units are simulated to ensure clear visualization of individual SOC trajectories, the proposed lower layer control law is fully decentralized, each unit requires only its local SOC and the globally averaged SOC (obtainable via broadcast or distributed consensus). The computational complexity per unit remains constant, and the communication overhead scales linearly with the cluster size, rendering the strategy inherently scalable to large-scale energy storage clusters.

– Case1 System Robustness Analysis under Step Disturbance

To evaluate the frequency support capacity and power allocation characteristics of the proposed strategy under sudden faults, a 10 MW step load disturbance was applied at t = 5 s. The system frequency response and thermal storage power allocation curves are shown in Fig. 2.

As seen in Fig. 2(a), in the face of large disturbances, the lowest point of the system frequency is effectively controlled within the allowable range, and no secondary drop phenomenon occurs, indicating that the proposed strategy meets grid frequency safety standards. Figure 2(b) clearly demonstrates the mechanism of “hierarchical cooperation”: at the instant the disturbance occurs, the energy storage cluster (blue curve) rapidly increases the power output to compensate for the deficit relying on its millisecond-level response; subsequently, as the thermal unit output (red curve) slowly increases, the energy storage smoothly withdraws, reflecting good complementary characteristics. Furthermore, Fig. 2(c) shows the SOC trajectories of individual batteries. It can be seen that even under continuous discharging conditions, the decline slope of batteries with a higher initial SOC is significantly greater than that of low-SOC batteries. This asymmetric discharge rate proves that the strategy can dynamically balance the states among units even when dealing with sudden faults.

– Case2 System Response under Continuous Fluctuation

To verify the comprehensive performance of the proposed strategy under complex conditions, a continuous fluctuating load composed of multiple superimposed sine waves was introduced in the simulation to simulate the random power impact of renewable energy in the actual grid [11]. The system frequency response, thermal storage power allocation, and the SOC evolution process of the distributed storage cluster are shown in Fig. 3.

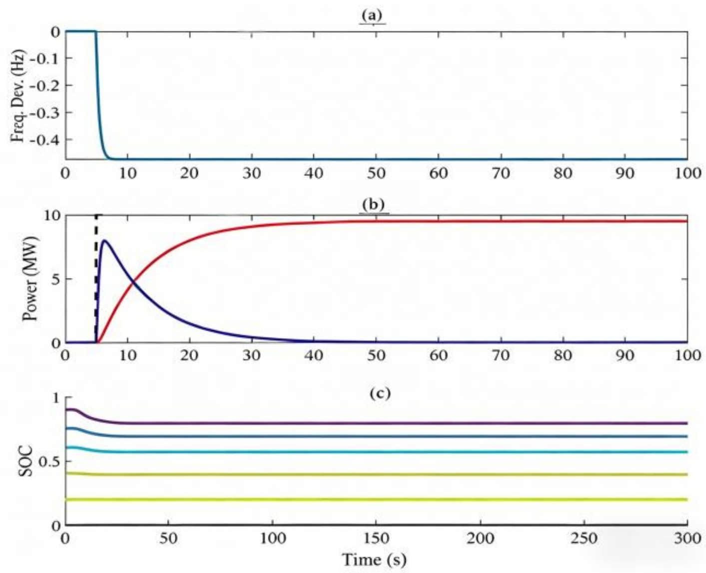

Fig. 2. System dynamic response under step disturbance: (a) System frequency step response; (b) Thermal storage power allocation; (c) SOC consistency under continuous discharge.

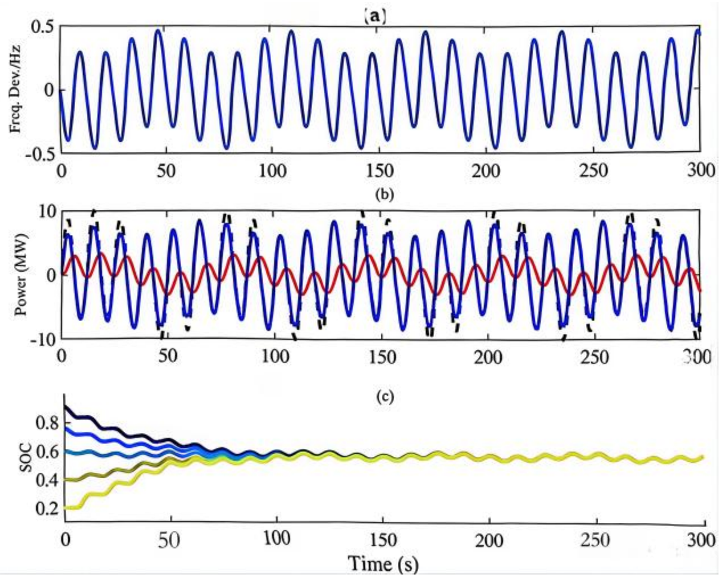

Fig. 3. Comprehensive system dynamic response under continuous fluctuation: (a) System frequency response; (b) Thermal storage power allocation; (c) SOC consistency convergence process.

As seen in Fig. 3(a), although the load disturbance changes frequently, the system frequency deviation is always limited within a small range of 0.05 Hz, and no significant oscillation divergence appears, proving the good dynamic stability of the control system. Figure 3(b) further reveals the effectiveness of the upper layer strategy in the dual-layer architecture: the thermal unit (red curve) mainly undertakes the smooth low-frequency component, avoiding mechanical wear caused by frequent ramping; while the storage cluster (blue curve) quickly responds to high-frequency glitches, precisely filling the power deficit and achieving complementary advantages of thermal and storage resources. Figure 3(c) intuitively displays the core effect of the lower layer consistency strategy. At the initial stage of simulation, the SOC of the five battery units presents a highly discrete state. As the frequency regulation process continues, the proposed adaptive weight algorithm begins to take effect: the decline rate of units with higher initial SOC during the discharge phase is significantly faster than that of low-SOC units. This adaptive adjustment mechanism of “those with higher charge output more, those with lower charge output less” makes the five SOC trajectories initially dispersed gradually move closer to the center. By the middle and late stages of the simulation, the SOC of each unit basically tends to be consistent, eliminating state differences among individual units. This indicates that the strategy effectively prevents individual units from withdrawing due to early depletion, thereby maximizing the overall available capacity of the storage cluster. Although Fig. 3(c) intuitively shows the trend of the aggregation of the SOC trajectories, to further quantitatively evaluate the precision and speed of convergence of the proposed strategy in consistency control, this paper introduces the SOC standard deviation σ_{SOC} as an evaluation index. Its curve over time is shown in Fig. 4.

As shown in Fig. 4, the SOC standard deviation presents a significant monotonic decreasing characteristic. In the early stage of the simulation, due to the large internal state difference of the storage cluster (the maximum deviation of the SOC reaches 0.7), the non-linear weight function in the lower layer controller exerts a strong adjustment effect, causing the standard deviation to rapidly drop from 0.25 to below 0.05, reflecting the algorithm's capability of rapid response in the face of extreme unbalanced conditions.

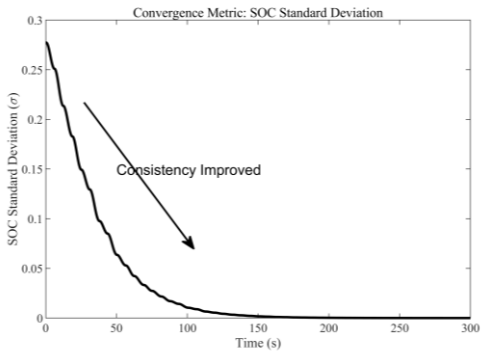

Fig. 4. SOC standard deviation curve.

As the regulation process continues, the states of the units gradually converge and the standard deviation curve smoothly converges and finally stabilizes at the magnitude of 10^{-3}. This quantitative result strongly proves that the proposed hierarchical cooperative strategy not only achieves the balancing of the state of the distributed storage cluster, but also has excellent convergence and robustness [11], fundamentally eliminating the short-board effect caused by individual differences and providing technical assurance for the long-term stable operation of the storage cluster [12].

V. CONCLUSIONS

Addressing the challenges of single-unit state mismatch and the "barrel effect" (short-board effect) when large-scale distributed energy storage clusters participate in grid frequency regulation, this paper constructs a system frequency response model based on discrete-time state space and proposes a hierarchical cooperative control strategy for thermal power and energy storage considering the consistency of SOC. When a two-layer control framework is constructed, the complementary advantages of different frequency regulation resources are realized effectively. The upper layer control utilizes a discrete filtering algorithm to make the thermal units focus on smooth low-frequency power support, avoiding mechanical wear; the storage cluster undertakes high-frequency power fluctuations, enhancing the system's dynamic response speed. The non-linear adaptive weight algorithm designed by the lower layer controller can dynamically reconstruct power allocation according to the real-time state of each unit without relying on complex global optimization. Research indicates that this strategy has an intrinsic negative feedback convergence mechanism, which is capable of driving heterogeneous storage units to achieve rapid SOC consistency convergence, thus maximizing the overall available capacity of the cluster. The proposed strategy effectively prevents unplanned withdrawal of single battery units due to overcharge or overdischarge while ensuring system frequency safety boundaries, achieving dual optimization of frequency regulation effectiveness and equipment safety. It provides a feasible engineering solution for distributed storage aggregation participating in ancillary services. Given the complexity of distributed energy storage and new power systems, future research will focus on as follows.

1. Cooperative Control under Communication Constraints: This paper assumes an ideal communication network. Future work will investigate in-depth the impact of communication delays, packet loss, and network topology switching on the convergence speed of the consistency algorithm and design distributed control protocols with stronger fault tolerance.
2. Lifecycle Optimization Considering Battery State of Health (SOH): Based on existing SOC consistency, further incorporate battery aging models and SOH indicators. Research how to balance SOC and SOH in power allocation to retard battery degradation, achieving comprehensive optimization of the economic benefits of frequency regulation and battery life cycle.
3. Integration with Grid-Forming Control: As grid inertia decreases further, research will combine the consistency algorithm with virtual synchronous generator (VSG) technology, enabling distributed storage clusters to actively provide inertia and voltage support while providing power support.

Moreover, beyond the aforementioned research directions, the integration of the proposed hierarchical control strategy with emerging trends in power systems warrants further investigation. Future work will explore the coupling of SOC-consistent control with electricity market mechanisms, enabling distributed storage clusters to provide frequency regulation as an ancillary service while optimizing economic returns. This involves developing bidding strategies that account for the dynamics of SOCs and degradation costs. Additionally, the increasing penetration of renewable energy introduces significant uncertainty; therefore, robust and stochastic optimization methods could be incorporated into the control framework to enhance resilience against forecast errors and extreme events. Another promising avenue is the extension of the current discrete-time model to a multi-rate or event-triggered framework, reducing communication and computation burdens while maintaining control performance. Finally, experimental validation on hardware-in-the-loop platforms or real-world microgrids will be conducted to verify the practical feasibility and scalability of the proposed strategy under realistic conditions, including communication imperfections and measurement noise. These efforts will collectively advance the readiness of distributed storage for large-scale deployment in future low-carbon power systems.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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