International Journal of Advanced Engineering Research and Science (IJAERS)
Peer-Reviewed Journal
ISSN: 2349-6495(P) | 2456-1908(O)
Vol-13, Issue-8; Aug, 2026
Journal Home Page Available: https://ijaers.com/
Article DOI: https://dx.doi.org/10.22161/ijaers.138.2

Comparison of Thermal Storage Combined Power Generation with Traditional Thermal Power Frequency Modulation and Generator Output

Lei Huang, Qiang-Sheng Xiao, Yan-Zuo Chang*

School of Energy and Power Engineering, Guangdong University of Petrochemical Technology, Maoming, Guangdong 525000, China
Email: 2951313200@qq.com
*Corresponding author: pangqu65165742@163.com

Received: 26 June 2026,

Received in revised form: 27 July 2026,

Accepted: 01 Aug 2026,

Available online: 06 Aug 2026

***Keywords*— Combined Thermal and Energy Storage System, Energy Storage System, Power Dispatching.**

***Abstract*— Faced with growing electricity demand, the frequency regulation capacity of traditional thermal power units is limited and difficult to meet the current power system. Combining thermal power units with energy storage facilitates flexibility upgrades by leveraging the ultra-fast response characteristics inherent to such system. The method of joint dispatching of thermal power and energy storage systems is called combined thermal and energy storage. This study develops a theoretical model of thermal-storage combined frequency regulation to analyze system dynamic responses. Combining lithium battery and flywheel energy storage systems with 1000MW thermal power units, a simulation model for dynamic frequency regulation and peak shaving was built in MATLAB/Simulink. The simulation experiments showed that the cooperative control strategy could enhance frequency regulation capacity and also improve the stability of thermal power units.*

I. INTRODUCTION

Under the goal of carbon peaking and climate neutrality goals, renewable energy sources have emerged as the central pillar of the modern power system, but new energy generation has obvious anti-peak shaving characteristics such as intermittency and volatility, which pose a serious threat to power system stability and power quality. Thermal power generation makes up 66% to 74% of the nation's total electricity output, capable of reliably supplying electricity to the grid, it is indispensable for maintaining the secure and steady performance of the power grid. With the growing penetration of renewable energy into the grid, thermal power units have problems such as poor regulation capacity, slow response speed, weak adaptability and insufficient frequency regulation capacity. Under normal circumstances, thermal power units have the highest operating efficiency under standard conditions, and their economic efficiency will decrease as the conditions change. The lower the operating load conditions and the larger the capacity of the unit, the lower the economic efficiency and safety. Thermal power units of the unit, the lower the economic efficiency and safety. When participating in frequency regulation and peak-shaving services, thermal power units are able to suppress frequency fluctuations and smooth system load curves through peak clipping and valley filling. Thermal power units are affected by mechanical response speed and thermodynamic characteristics. During frequency regulation and peak shaving, the power system has to reserve a large amount of rotational capacity, and the units usually do not operate under optimal load conditions, which greatly reduces safety and economy. Frequent power adjustments and start-stop operations aggravate equipment fatigue damage, shorten equipment inspection cycles, reduce fuel utilization, and increase system operating costs. According to statistics,15% to 20% of the operating costs of deep peak shaving and frequency regulation dominated by thermal power come from the input of rotating reserve capacity, energy utilization is reduced by about 10%, and the failure rate of equipment is increased by 2.1 times. Power system reliability is confronted with severe challenges, and thermal units require urgent improvement in flexibility. Nevertheless, thanks to their enormous installed capacity, such units possess great potential for flexibility retrofitting, which mainly involves retrofitting the units themselves. For example, the transformation of boilers and steam turbines, Ma, G. P.[Error! Reference source not found.] and Li, J.[Error! Reference source not found.] et al. conducted research on the stable combustion effect of micro-oil ignition technology, and Dong, Z. Z.[3] proposed the multi-energy storage coordinated dispatch control technology. Guo, Z. H. [Error! Reference source not found.] and D.[Error! Reference source not found.] Propose measures such as replacing the integral inner cylinder with multiple segmented retaining rings, implementing near-zero output modification for the low-pressure cylinder, and optimizing the startup plan. To some extent, it can enhance the capacity for peak shaving and frequency regulation, but it is still affected by cost and load.

Lithium battery systems can achieve bidirectional power regulation and millisecond-level response, charge and discharge in the instant of sudden changes in grid frequency, and have the characteristics of high-capacity density, long maintenance cycle, high voltage resistance, etc. But the battery's energy storage life and capacity are limited, making it difficult to handle large capacity tasks independently for long periods of time. Too high a frequency of deep charge and discharge can cause the device to age and shorten its lifespan. It is estimated that if the energy storage system charges and discharges more than three times a day, The equipment replacement cycle will shorten by 30% to 40%, leading to a significant increase in costs. Flywheel energy storage, which stores and releases energy through high-speed rotation, features a simple structure, ultra-low self-discharge and high energy conversion efficiency. However, it encounters obstacles including high manufacturing and maintenance costs, low energy storage density and short energy storage time. The energy storage system responds quickly but has a small capacity for regulation, while thermal power units have a large capacity for regulation but a slow speed. The principle of combined thermal and energy storage frequency regulation is to complement each other by taking advantage of their strengths. There are certain differences in response speed and service life among different energy storage systems. A key challenge in the coordinated operation of thermal power and energy storage systems is optimizing their performance in frequency regulation tasks. In the application of lithium battery energy storage in thermal power, Wang, M. S. et al. [9]proposed a frequency modulation control strategy based on a coordinated topological structure, the combined system could reduce the number of actions of the unit's steam valve, alleviate increased wear and tear, and extend the service life of the equipment. Zhou, J. et al.[5] control strategy for dynamic sag coefficient solves the problems of high response delay and small regulation range of traditional thermal power units, significantly enhancing the stability of the units. Zhang, P. and Liu, H. T.[6] proposed a flywheel-thermal power frequency regulation control strategy based on stepwise variational mode decomposition, which minimizes frequent adjustments of thermal units during frequency regulation, alleviates their regulation burden, and enhances the operational safety of the flywheel system.

II. PRINCIPLE

Primary frequency regulation refers to the automatic control process in which the control system of the units in the grid automatically controls the increase or decrease of the active power of the units when the grid frequency deviates from the rated value[Error! Reference source not found.], limits the change of grid frequency, and keeps the grid frequency stable. The actuation time of primary frequency regulation typically falls within the range of seconds to minutes, depending on the generating technology. In the event of a grid frequency increase, primary frequency regulation necessitates a rapid load reduction, achieved by utilizing the unit's internal heat storage capacity; conversely, the unit rapidly increases the load. Grid frequency is determined by the balance between the mechanical power input to the generators and the electrical power output demanded by the loads. When the power system is in a stable state, there are two static characteristic straight lines. As shown in Figure 1 below, line 1 represents the static frequency of the generator; Line 2 represents the total load static frequency. The generator's power-angle curve intersects with the mechanical power input line at the point where electrical output equals mechanical input, and they reach a delicate equilibrium point o, the frequency corresponding to the equilibrium point is called f_n. At some point, when the load suddenly increases, the static frequency line of the load shifts upward along the longitudinal axis as shown in line 3, and a new equilibrium point O is formed. At this point, the frequency of exceeds the maximum threshold range, and the generator increases the active power to stabilize the frequency within 50HZ (±0.2HZ).

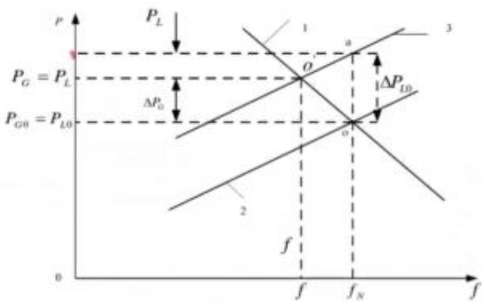

Fig. 1: Static P-f Characteristics

Primary frequency regulation significantly impacts the unit's operating conditions. When grid frequency drops, the unit increases output by opening the turbine valves, which causes a rapid increase in steam flow and consequently drops the main steam pressure. At this point, the boiler needs to burn more fuel to maintain the pressure balance. During this period, there will be huge fluctuations in thermal stress, and frequent adjustments will not only intensify the damage to the equipment and shorten its service life, but also reduce the fuel utilization rate and increase the power consumption of the plant. To address these issues, many scholars have delved deeply into the technology of combined thermal storage frequency regulation systems. In the combined system, When the ramping capability of thermal units cannot match the rapid changes in grid demand, the energy storage system provides a fast response, thereby compensating for the limitations of thermal power generation.

III. MODEL BUILDING

To better analyze the performance of combined thermal-storage frequency regulation, this paper develops detailed simulation models in MATLAB/Simulink and carries out comprehensive simulations to verify its advantages over traditional thermal-only regulation.

3.1GOVERNOR MODEL

As the core equipment of the thermal power generation control system, the thermal power unit governor realizes its core function to precisely control the unit speed and active power output by regulating the steam intake of the steam turbine. Specifically, when the unit speed changes, the governor controls the steam intake of the steam turbine. When the frequency increases, the governor will reduce the opening of the main steam inlet, decrease the steam intake, and cause the frequency to fall back; Conversely, when the frequency drops, increase the steam intake to bring the frequency back up. Figure 2 shows a simple control model, and the rotational speed is adjusted to maintain a dynamic balance between mechanical power and electromagnetic power, ensuring grid stability and power quality.

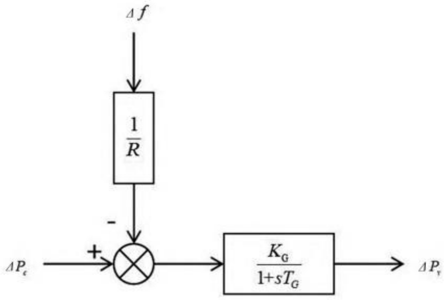

Fig. 2: Simplified Governor Model

Its transfer function can be expressed by formula (1) as:

$$\Delta P_v = \frac{K_G}{1+sT_G}\left(\Delta P_c - \frac{1}{R}\Delta f\right) \tag{1}$$

In Formula (1), the governor deviation coefficient is R, the governor time constant is T_G, the governor static gain coefficient is K_G, the governor valve position change is △Pv. The system control signal is △Pc, the transfer function of the governor is Gg(S), and the frequency deviation is △f.

3.2 REHEAT TURBINE MODEL

The steam valves and pipes of the steam turbine together form a specific volume of space during the operation of the thermal power unit. The volume of gas in the pipe varies with the opening of the gas valve. Because the pressure at the valve cannot change abruptly, when the steam flow changes at a certain moment and the pressure cannot change accordingly, the mechanical power changes cannot keep up with the changes in the valve opening, resulting in a lag in the mechanical power changes. Introducing the first-order inertial link to study the dynamic characteristics, in order to improve the energy conversion efficiency, the reheat pipe inside the steam turbine transfers the steam to different working stages. Due to the time required for steam transfer, there will inevitably be delays. To ensure the precision of the thermal power unit model, this effect must be incorporated into the model. The model of the reheat turbine is shown in Figure 3.

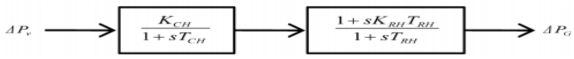

Fig. 3： Reheat Steam Turbine Dynamic Model

The transfer function is as shown in formula (2):

$$G_T(s) = \frac{\Delta P_G}{\Delta P_v} = \frac{K_{CH}(1+sK_{RH}T_{RH})}{(1+sT_{CH})(1+sT_{RH})} \tag{2}$$

In Formula (2): $\triangle P_G$ is the change in output power of the steam turbine, T_{CH} is the volumetric time constant, K_{CH} is the gain coefficient of the steam turbine, T_{RH} is the reheat time constant, K_{RH} is the reheat gain coefficient.

3.3GENERATOR MODEL

When there is an external disturbance or an internal load fluctuation, the power system frequency deviates from its rated value. In modern power system analysis, when multiple generators are in the same area, they can be equivalent to one equivalent generator with the same parameters. The power system - equivalent generator model is shown in Figure 4.

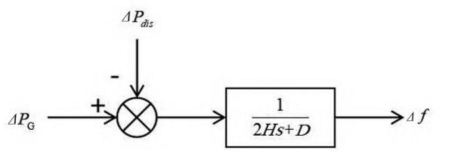

Fig. 4: equivalent generator model

The transfer function is as shown in Formula (3):

$$G_P(s) = \frac{\Delta f}{\Delta P_G - \Delta P_{dis}} = \frac{1}{2Hs+D} \qquad (3)$$

In Formula (3) : $\triangle$Pdis is the active power disturbance of the system, H is the inertia time constant of the power system, and D is the load regulation coefficient of the power system.

3.4.1 BATTERY ENERGY STORAGE MODEL

With the advancement of modeling techniques, the electrical characteristics, electrochemical properties, and advanced algorithms of battery energy storage have become popular research hotspots. This paper, nevertheless, focuses exclusively on frequency regulation and peak shaving demands., does not consider the internal conversion process of energy storage batteries, only considers the external characteristics. The dynamic relationship between the output power of the battery energy storage system and the control signal is characterized by a first-order lag. The corresponding battery model is illustrated in Figure 5.

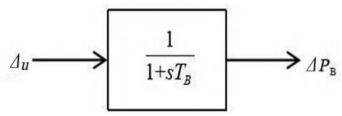

Fig. 5: Lithium Battery Energy Storage Model l

The transfer function is as shown in formula (4):

$$G_b(s) = \frac{\Delta P_B}{\Delta u} = \frac{1}{1+sT_B} \qquad (4)$$

In Formula 4: $\triangle P_L$ is the output power of the energy storage battery, $\triangle$u is the control signal of the energy storage battery, and T_{BL} is the response time constant of the energy storage battery.

State of charge calculation formula (5):

$$\mathrm{SOC} = \mathrm{SOC}_0 - \left(\int_0^t N_f \mathrm{d}t\right)/E \qquad (5)$$

SOC_0 is the initial state of charge for energy storage. E is the total amount of energy stored. P_L is the real-time output power.

3.4.2 FLYWHEEL ENERGY STORAGE SYSTEM MODEL

Flywheel energy storage is a form of inertial energy storage where the flywheel stores or releases energy by rotating. When the frequency rises, electrical energy drives the flywheel to rotate, converting the excess electrical energy into mechanical energy; Conversely, when the frequency drops, the flywheel drives the motor to generate electricity, converting mechanical energy into electrical energy. Since the generator unit in the flywheel energy storage system is typically a Permanent Magnet Synchronous Motor (PMSM), its electrical dynamics can be modeled using the standard PMSM equations, as shown below:(6) - (9)

Stator voltage:

$$\begin{cases} u_d = \dfrac{d\psi_d}{dt} + R_s i_d - \omega_e \psi_q \\ u_q = \dfrac{d\psi_q}{dt} + R_s i_q + \omega_e \psi_d \end{cases} \qquad (6)$$

Flux linkage equation:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \qquad (7)$$

Electromagnetic torque:

$$\begin{cases} T_e = 1.5 n_p (\psi_d i_q - \psi_q i_d) \\ P_e = T_e \omega_e \end{cases} \qquad (8)$$

Flywheel model:

$$J \frac{d\omega_m}{dt} = T_e - T_L - B\omega_m \qquad (9)$$

Formula for calculating state of charge (10):

$$\mathrm{SOC} = \mathrm{SOC}_0 - \left(\int_0^t N_f \mathrm{d}t\right)/E \qquad (10)$$

3.5 ENERGY STORAGE CONTROL STRATEGY

Build the structure diagram as shown in Figure 6 in Simulink, this study employs a piecewise smooth transition control strategy, which is based on key parameters such as the State of Charge (SOC) and power deviation. First, the positive and negative deviation signals of the input are converted into a uniform non-negative signal in the energy storage signal preprocessing module, facilitating threshold switching. Set the threshold safety boundary of the soc to 0.275, 0.450, 0.550, etc.

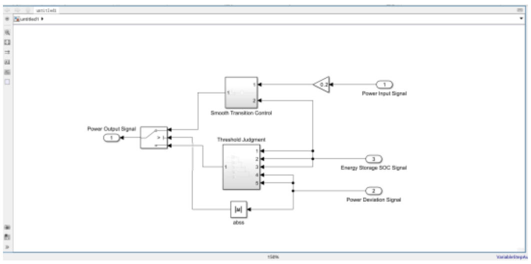

Fig. 6 Structure Diagram of Energy Storage Control Strategy:

Introduce two control modes during charge and discharge to control the soc value. One is smooth transition control, which eliminates impulse during threshold switching and uses sigmoid to achieve power "soft switching" in the threshold critical interval; Another is threshold judgment, where in the safe zone, when the soc value changes, The charging and discharging power will increase or decrease linearly accordingly. At the critical interval, the parameters are close to the threshold, dominated by smooth transition control, eliminating the risk of sudden changes through nonlinear functions; In the safety zone, the system state is stable, dominated by threshold judgment, with efficient regulation capabilities. The dominance of the control strategy at different soc values is shown in Table 1.

Table. 1: Application of Charging and Discharging Scenarios and Control Strategies

SOC Value	Threshold Judgment	Smooth Transition Control
0.100 ~ 0.275	Not involved	Dominant
0.275 ~ 0.450	Dominant	Not involved
0.450 ~ 0.550	Dominant	Not involved
0.550 ~ 0.725	Dominant	Not involved
0.725 ~ 0.900	Not involved	Dominant

Linear computations are time- consuming, simple and efficient, which is an advantage of threshold judgment, suitable for safe and stable state intervals; Nonlinear functions that eliminate abrupt shock are an advantage of smooth transition control and are suitable for critical intervals near the threshold. The parameter ranges of both are perfectly connected, ensuring regulation efficiency under operating conditions and achieving soft switching to eliminate shock at the threshold boundary. Strike a balance between "safe operation" and "quick response" for the system.

1. ENERGY STORAGE SYSTEM SUPPORT FOR FREQUENCY REGULATION

The example used here is the parameter of a certain power plant unit in Hubei Province. The specific values of the simulation parameters are provided in Table 2

Table. 2: Some simulation parameters

Parameter	P_E	T_{CH}	T_{RH}
Value	1000MW	0.2s	6s

Table (continued)

Parameter	**H**	**R**	T_C
Value	0.06pu/s	3HZ/pu	0.3s
Parameter	D	K_{RH}	
Value	0.009pu/HZ	0.3pu	

The energy storage system assistance was divided into two groups, one with thermal power combined with 18MW/16MWh lithium batteries and the other with thermal power combined with 18MW/16MWh flywheels, and both groups were compared with thermal power unit frequency regulation alone. Build the Figure 7 model with MATLAB/Simulink for 1500s, and add 10MW and 15MW load disturbances at 1200s.

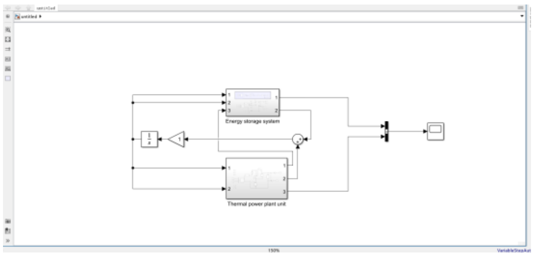

Fig. 7: Models of Thermal Power Units and Energy Storage Systems

The frequency variations are shown in Figures 8 and 9, while the output power of the thermal units is presented in Figures 10 and 11.

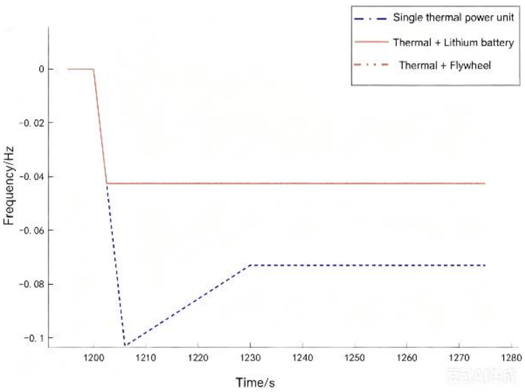

Fig. 8: Comparison of frequency curve changes under 10MW load disturbance

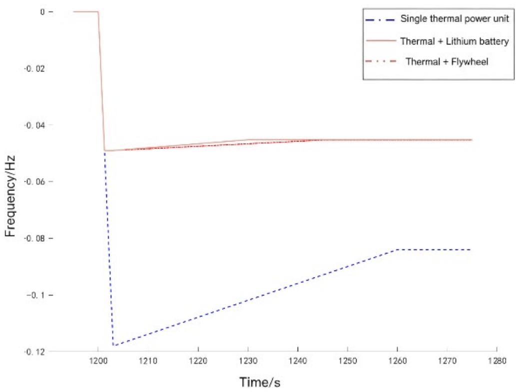

Fig. 9: Comparison of frequency curve changes under 15MW load disturbance

As illustrated in the two graphs above, introducing an energy storage system to assist traditional thermal power units significantly enhances frequency regulation capacity, regardless of the magnitude of load disturbance. There is little difference in performance between flywheel and lithium battery-assisted systems, except for a slight divergence in the later stages of regulation due to differences in response speed. Once the frequency stabilizes, both systems converge to the same final frequency. Specifically, under a 10 MW load disturbance, the frequency deviation of the standalone thermal unit is -0.073 Hz, whereas the combined system reduces this to -0.0425 Hz. When the disturbance increases to 15 MW, the thermal unit's deviation worsens to -0.084 Hz, while the combined system maintains a deviation of only -0.0453 Hz, demonstrating a significant improvement in frequency regulation effectiveness.

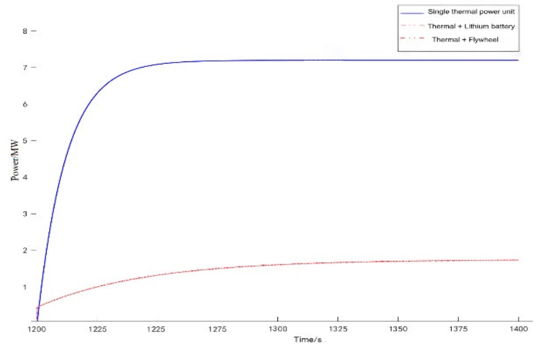

Fig. 10: Comparison of Thermal Unit Output Power under a 10 MW Load Disturbance

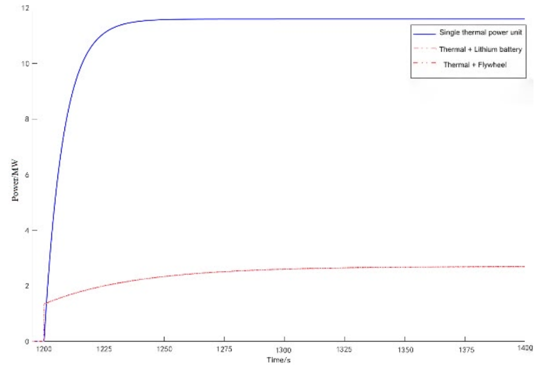

Fig. 11: Comparison of Thermal Unit Output Power under a 15 MW Load Disturbance

As illustrated in the figure above, combined frequency regulation offers clear advantages over regulation performed solely by thermal power units. It not only improves the overall frequency response capability but also significantly reduces the output burden placed on thermal units during grid disturbances. When a disturbance occurs, a thermal unit operating independently tends to increase its output in line with rising load demand. This often forces the unit to sustain high power levels for prolonged periods, which accelerates component wear and shortens its service life.

Quantitative data further supports this conclusion. Under a 10 MW load disturbance, the thermal unit alone delivers 7.265 MW, leaving a deficit of 2.735 MW. When the disturbance rises to 15 MW, the unit's output reaches 11.513 MW, with the shortfall widening to 3.487 MW, and the output increment between the two cases is 4.248 MW. In contrast, under combined regulation, the thermal unit produces only 1.834 MW at 10 MW disturbance and 2.594 MW at 15 MW, with an increment of just 0.76 MW. This represents a substantial reduction of 82.1% in thermal output compared to the standalone mode.

Moreover, when a thermal unit is operating normally and suddenly receives a load regulation command, the integrated energy storage system enables more precise frequency adjustments. It ensures that the unit remains stable while meeting dynamic grid requirements. Overall, combined frequency regulation provides a more efficient, durable, and responsive solution, effectively balancing performance and equipment protection in modern power systems.

.

IV. CONCLUSION

Based on theoretical foundations, this paper develops several models, including those for the governor, steam turbine, and energy storage systems. Specifically, a 1000 MW thermal power unit is integrated with an 18 MW/16 MWh flywheel energy storage system and a lithium battery energy storage system. Simulation experiments are conducted in MATLAB/Simulink to evaluate frequency regulation performance under various operating conditions, with comparisons made against traditional thermal power alone.

The simulation results demonstrate that when the system experiences external disturbances, the combined configuration responds more rapidly and achieves smaller frequency deviations after regulation than the conventional thermal unit. This clearly highlights the superiority of the hybrid approach in maintaining grid frequency stability.

Furthermore, as the disturbance magnitude increases, the output increment of the thermal unit within the combined system does not rise correspondingly. This indicates that the energy storage effectively absorbs the additional regulation burden. When the thermal unit suddenly receives a load adjustment command, the integrated storage system can significantly mitigate output fluctuations, thereby facilitating the recovery of the unit's stored energy and protecting critical equipment from excessive stress.

In summary, the combined thermal-storage system exhibits marked improvements in regulation accuracy, operational safety, and overall stability compared to a standalone thermal power unit. These findings confirm that the synergy between thermal generation and energy storage offers a more reliable and resilient solution for modern power system frequency control.

ACKNOWLEDGEMENTS

This work was supported by the Research Funding of GDUPT. “Research on Heat Transfer Enhancement of Heat Sink by Inverse Calculation Design Method" (No. 2019rc074).

REFERENCES

[1] Ma, G. P. (2008). Reliability of zero-fuel operation and standby mode of plasma ignition and stable combustion system for boiler in Huilai Power Plant. *China Electric Power*, (3), 53–57.

[2] Li, J., Xiong, J. G., Tong, J. L., et al. (2018). Research on boiler's ultra-low load stable combustion technology in deep peak regulation. *Zhejiang Electric Power*, 37(2), 62–66. DOI: 10.19585/j.zjdl.201802013.

[3] Dong, Z. Z. (2021). Research on control technology for multi-energy storage coordinated dispatch of 600 MW subcritical units. *Electric Power Journal*, 36(6), 573–586. DOI: 10.13357/j.dlxb.2021.069.

[4] Guo, Z. H., Zhang, Q., Xiong, N., et al. (2020). Analysis of thermal performance of the low-pressure cylinder of a 330 MW heating unit at nearly zero output. *Chemical Engineering Progress*, 39(9), 3650–3657. DOI: 10.16085/j.issn.1000-6613.2019-1581

[5] Zhou, J., Shi, S. C., Qi, F. Z., et al. (2024). Research on the control strategy of energy storage battery assisted secondary frequency regulation for coal-fired power units. Chinese Testing, 50(10), 51–58.

[6] Zhang, P., & Liu, H. T. (2024). A fly-wheel–firepower primary frequency regulation control strategy based on successive variational mode decomposition. *Global Energy Interconnection*, 7(2), 166–178. DOI: 10.19705/j.cnki.issn2096-5125.2024.02.006

[7] Bu, Z. B., Jiang, D. W., Wang, S., et al. (2026). Power balance allocation method for hybrid energy storage system containing lithium batteries and supercapacitors. Electrical Industry, (1), 95–99.

[8] Li, X. T., Chen, L., Hao, L., et al. (2023). A combined primary frequency regulation control strategy for thermal power and storage based on two rules. High Voltage Engineering, 49(10), 4163–4171. DOI: 10.13336/j.1003-6520.hve.20230929

[9] Wang, M. S., Jiang, L. B., Xu, Y. R., et al. (2025). Frequency regulation control strategy for reconfigurable battery energy storage system based on coordinated topology structure. Distributed Energy, 10(6), 54–61。

[10] Checcacci, D., Cosi, L., & Sah, S. K. (2011). Rotor life prediction and improvement for steam turbines under cyclic operation. In Turbo Expo: Power for Land, Sea, and Air (Vol. 54679, pp. 2371–2379). ASME.

[11] Shen, C. Q., Shu, G. Y., Cheng, J. Y., et al. (2015). A fast-transition slow-recovery one-time frequency regulation strategy. *Automation of Electric Power Systems*, 39(13), 158–162.