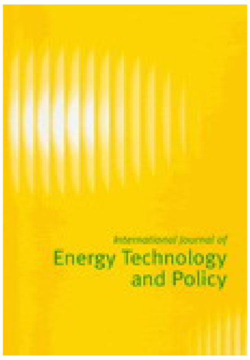


**International Journal of Energy Technology and Policy**

ISSN online: 1741-508X - ISSN print: 1472-8923
https://www.inderscience.com/ijetp

# Methods of realising grid frequency modulation by using adiabatic electromagnetic compressed-air energy storage

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**DOI:** 10.1504/IJETP.2025.10073801

**Article History:**

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|---|---|
| Received: | 29 April 2025 |
| Last revised: | 06 August 2025 |
| Accepted: | 19 August 2025 |
| Published online: | 31 October 2025 |

# Methods of realising grid frequency modulation by using adiabatic electromagnetic compressed-air energy storage


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**Abstract:** To address the issue of increased frequency fluctuations in the power grid following the integration of a high proportion of renewable energy sources, this paper develops a frequency regulation (FM) control model for an adiabatic electromagnetic compressed air energy storage system (CAES). Simulation results show that when the disturbance intensity is 0.02 p.u., for strategy 1, the frequency deviation (FD) of the proposed method is ±0.011 p.u., with a response time of only 0.477 seconds; for strategy 2, the frequency modulation (FM) accuracy of the proposed method is ±0.031 p.u., with a response time of 0.79 seconds. The research results show that an adiabatic electromagnetic compressed air energy storage system can effectively improve the frequency regulation accuracy and response speed of the power grid, providing a stable and efficient frequency regulation method for power grids with a high penetration of renewable energy sources.

**Keywords:** grid frequency modulation; frequency control strategy; adiabatic electromagnetic compressed-air energy storage; frequency stability; energy storage and release optimisation; short-time Fourier transform; STFT.

**Reference** to this paper should be made as follows: Zhang, L., Wang, B., Li, Y., Zhu, X., Qu, Z. and Zhong, H., (2025) 'Methods of realising grid frequency modulation by using adiabatic electromagnetic compressed-air energy storage', *Int. J. Energy Technology and Policy*, Vol. 20, No. 6, pp.90–118.

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## 1 Introduction

The global energy transition has connected a large number of renewable energy sources to the power grid, posing challenges to the frequency stability of the power grid (Alqahtani et al., 2023; El-Bahay et al., 2023; Saleem et al., 2024). The traditional power grid FM method has slow response and low accuracy, making it difficult to cope with fluctuations in power generation, which affects the stable operation of the system (Ashouri-Zadeh et al., 2020; Wu et al., 2022; Yuan et al., 2022). In this context, improving the speed and accuracy of FM response has become a hot topic in research. Adiabatic electromagnetic compressed air energy storage technology combines electromagnetic regulation with advanced energy storage principles to efficiently store and release energy. It optimises the compression process, reduces heat loss, and uses intelligent control strategies to improve response speed and stability. It is suitable for the frequency regulation needs of power grids with a high proportion of new energy access, and has broad application prospects and development potential. The existing FM methods can no longer meet the needs of fast and efficient operation, and new methods are urgently needed to enhance the power grid frequency stability (Hong et al., 2023). This article studies the problem of power grid FM, especially how to use new energy storage technology to optimise FM in the context of a high proportion of renewable energy. In practical applications, adiabatic electromagnetic CAES systems face challenges such as low energy conversion efficiency, system response delay, high equipment cost, and insufficient operational stability. By optimising thermodynamic models, introducing advanced materials and intelligent control algorithms, system efficiency and response speed can be improved; modular design can be used to reduce construction and maintenance costs; and real-time monitoring and predictive control strategies can be combined to enhance system stability and reliability, thereby promoting its widespread application in power grid frequency regulation.

This article proposes a FM method based on adiabatic electromagnetic CAES and constructs a dynamic model of adiabatic electromagnetic CAES. Energy storage and release are optimised, and a FM control strategy that quickly responds to grid frequency fluctuations is designed. When the FD occurs, this strategy quickly uses adiabatic electromagnetic CAES to release energy compensation, significantly improves the FM response speed and accuracy, and solves the problem of traditional thermal power units. Experimental results show that this method effectively reduces frequency fluctuations and enhances the stability of power grid FM. The research focuses on further optimising the energy conversion efficiency of adiabatic electromagnetic CAES, reducing costs, and promoting its widespread application in power grid FM. Meanwhile, more advanced control strategies are explored to ensure the stable and efficient operation of energy storage systems and provide stronger support for power grid FM. The innovation of this article is to optimise the performance of the compressor and achieve efficient energy storage and release by applying the entropy efficiency correction equation. At the same time, combining the laws of thermodynamics and the non-ideal gas equation, a mathematical model is established to enhance energy utilisation, and the state of the gas tank is monitored in real-time to optimise efficiency. An energy release strategy is designed based on predictive control, and PID control and dynamic weighting are adopted to enhance the system's adaptability to different disturbances and ensure smooth energy release.

The main contribution of this paper is to propose an innovative power grid frequency modulation solution, which significantly improves the frequency stability and frequency modulation response efficiency of the power grid through the adiabatic electromagnetic CAES system. First of all, the FM control model of the adiabatic electromagnetic CAES system is constructed, which optimises the rapid energy release and dynamic power adjustment functions, and solves the problem of slow response and low accuracy of the traditional FM method; secondly, through the entropy efficiency correction equation and the non-ideal gas equation, a mathematical model to reduce heat loss is established and the energy utilisation rate of the gas storage tank is improved; furthermore, the LSTM model is used in combination with wavelet transform for load prediction, and an energy release strategy based on predictive control is designed to enhance the system's adaptability to different disturbances; in addition, a control strategy based on real-time frequency offset is proposed, using STFT and EWMA technologies. The millisecond response is realised and the frequency modulation accuracy is improved; finally, an adaptive frequency modulation algorithm is designed, and the PID parameters are dynamically adjusted using the recursive least squares method to enhance the adaptability and stability of the system. The experimental results show that this method performs well in terms of frequency modulation accuracy, response speed and power grid load adaptability, effectively responds to the challenges posed by the uncertainty of new energy sources, and provides a stable and efficient frequency modulation method for power grids with a high proportion of new energy sources connected to the grid.

## 2 Related work

Although the traditional power grid FM method has a certain effect, its shortcomings gradually become apparent when the proportion of renewable energy increases (Elkasem et al., 2024; Milano and Ortega, 2020). To solve this problem, many scholars have proposed different new FM methods. Chen et al. (2023) proposed a two-layer optimisation strategy for a battery energy storage system to achieve primary FM of the power grid to solve the frequency fluctuation problem caused by the dynamic power imbalance between the power system and the load when a large number of renewable energy sources are connected to the power grid. The rapid development of new energy has had a profound impact on the existing power grid structure. Han and Liu (2023) proposed a lithium battery flywheel joint control strategy and a regional dynamic primary FM model for thermal power generation units. The frequency regulation performance is evaluated through indicators such as system frequency fluctuation amplitude and fluctuation peak range, providing a scientific basis for optimising energy allocation. In order to reduce the fatigue load on the shaft system, energy storage is added to the primary frequency regulation of wind turbines. Zhang et al. (2024a) proposed a fuzzy control-based wind energy storage coordinated frequency regulation control strategy, which can reduce the load pressure and fatigue damage of the shaft system while meeting the frequency regulation requirements. In order to accurately predict the primary frequency regulation capability of the power system during frequency offset, Zhang et al. (2023a) proposed a method for predicting the primary frequency regulation performance of the power system based on an improved neural network using a thought evolution algorithm. This method can assist power dispatchers in analysing the primary frequency regulation response of the power grid after power disturbances. Huang et al. (2024) used the VSG Shichengzi Photovoltaic Power Station unit as an example to introduce in detail the significance, principles, and measures of implementing primary frequency regulation in the power station, and proposed a suitable primary frequency regulation test technology scheme and test method for photovoltaic power stations. The above-mentioned scholars have proposed different innovative control strategies or architectures to solve the frequency fluctuations caused by the integration of new energy into the power grid, and verified their effectiveness in improving grid stability. However, most of these methods are targeted at specific energy storage or power generation systems, and their widespread applicability needs to be improved. However, their long-term stability and cost-benefit analysis are still insufficient.

In response to these problems, CAES technology has been more widely studied and applied in recent years. CAES can achieve efficient storage and rapid energy release by combining CAES with an electromagnetic regulation mechanism (Cui et al., 2024; Li et al., 2021). Guo et al. (2023) summarised the coupling systems of CAES with wind energy, solar energy, and biomass energy from the perspective of system topology, and pointed out the advantages and limitations of each system. The coupling of wind energy and compressed air energy storage mainly adopts series and parallel methods, and sometimes, some wind power can be converted into thermal energy when coupled to compressed air energy storage. In order to utilise the effectiveness of different types of energy storage in increasing grid frequency in frequency regulation of the power system, Zhang et al. (2023b) carefully studied the capacity allocation of hybrid energy storage power stations when participating in grid frequency regulation. A regional model of a hybrid energy storage primary FM system was established using Simulink. Due to the limitations of conventional energy supply, the power grid is facing difficulties. Das and Kumar (2024) present an innovative model that utilises the ideal scheduling of a wind farm (WF)-CAES fuel cell hybrid system to improve the system's economic profitability while keeping the grid frequency within a safe range. In response to the shortcomings of compressed air energy storage systems in emergency response research for power assistance, Wu et al. (2025) established an energy release stage model for a 10 MW compressed air energy storage system equipped with an anti overspeed system, mainly focusing on decoupling the speed control of the two stages of the compressed air energy storage system: surge speed and system recovery standby. With the increasing proportion of new energy generation in the power grid, higher requirements have been put forward for the time scale of the energy release process in energy storage systems. Yang et al. (2023) proposed a novel compressed air energy storage system with injectors and burners to achieve short-term and long-term energy release processes under non-supplementary combustion conditions and injector supplementary combustion conditions, respectively. Scholars have explored the application of CAES in power grid frequency regulation and proposed specific solutions to improve system design and efficiency. However, the study focuses more on technological improvements. In practical power grid frequency regulation problems, its long-term reliability still needs further verification.

## 3 Dynamic modelling and control strategy of adiabatic electromagnetic CAES system

### *3.1 Modelling of adiabatic electromagnetic CAES system*

To effectively respond to grid frequency fluctuations, there is a need to first build a precise dynamic mathematical model for the adiabatic electromagnetic CAES system.

**Figure 1** Model diagram of adiabatic electromagnetic CAES system

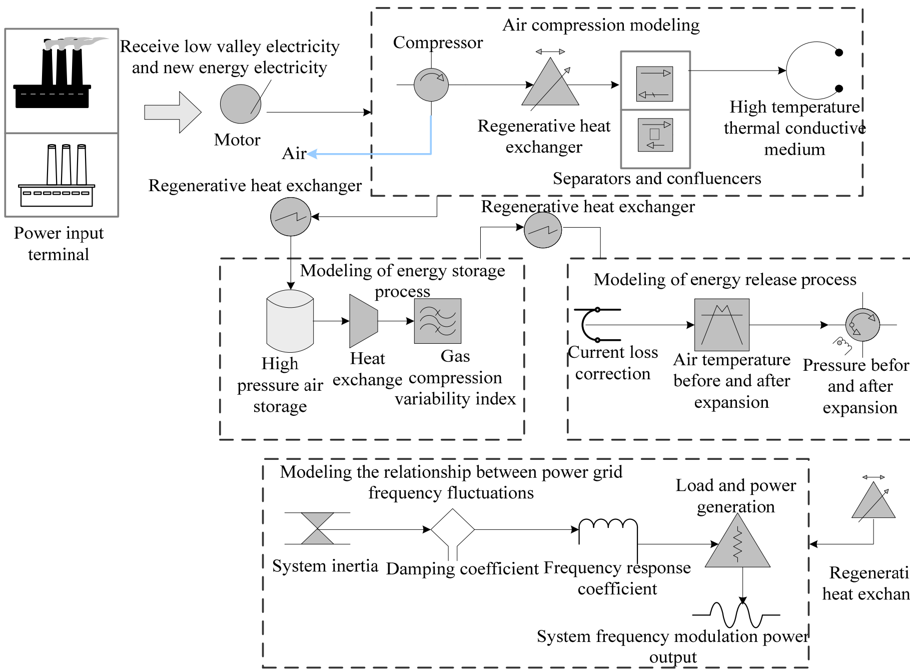



Figure 1 shows the model of the adiabatic electromagnetic CAES system, which can respond to the frequency fluctuations of the power grid, including three stages of air compression, energy storage and release, and interacts with the frequency of the power grid. All stages are subject to thermodynamic constraints and consider the actual efficiency correction. During storage, the conditions are optimised through heat exchange to reduce losses, and the high-pressure air is converted into electrical energy when released.

#### *3.1.1 Modelling of air compression process*

In the adiabatic electromagnetic CAES system, the air compression stage is the key to converting electrical energy into mechanical energy, which affects the overall energy conversion efficiency (Barbour and Pottie, 2021; Floris et al., 2023; Yin et al., 2020). The air is efficiently compressed and stored, providing a stable high-pressure air source for subsequent energy release. Under ideal reversible conditions, the thermodynamic equation of the compressor can be expressed as equation (1):

$$Q_{comp} = \dot{n} d_q R_0 \left( \left( \frac{q_1}{q_0} \right)^{\frac{\beta-1}{\beta}} - 1 \right) \tag{1}$$

Among them, $Q_{comp}$ – the compression power; $\dot{n}$ – the air mass flow rate.

However, when air flows in the compressor, it is affected by friction, heat conduction, and flow loss, and it is difficult to reach the ideal entropy state. Therefore, the entropy efficiency $\tau_{comp}$ is often used in engineering calculations to correct the ideal power and obtain the actual compression power consumed, as shown in equation (2):

$$Q_{comp,real} = \frac{Q_{comp}}{\tau_{comp}} \tag{2}$$

Among them: $\tau_{comp}$ – the efficiency of the compressor during actual operation, which is generally calculated based on experimental detection or statistical data.

The entropy efficiency correction equation is derived based on the second law of thermodynamics and is used to describe the impact of irreversible losses on efficiency during the actual compression process. Its physical meaning is to correct the ideal compression work through the entropy production rate, making the model closer to the actual working conditions and improving the prediction accuracy of the system energy conversion efficiency.

The modified equation provides a more accurate description of energy conversion in air compression stages, where temperature and pressure variations in gas storage tanks are critical for the stability of adiabatic electromagnetic CAES systems. Energy loss during adiabatic compression is commonly mitigated through measures like intercooling to reduce outlet temperatures (Pottie et al., 2023; Tola et al., 2022; Wang et al., 2025). Establishing a multi-factor mathematical model can provide theoretical support and precise descriptions for operational control and grid frequency regulation, ensuring stable system operation.

### *3.1.2 Energy storage process modelling*

In adiabatic CAES systems, the energy storage component connects compression and energy release processes, which are critical for efficiency and stability (Chen et al., 2020; Zhang et al., 2020). Compressed high-pressure air is stored in insulated containers to provide energy. The energy storage process requires integration of the first law of thermodynamics with gas state changes, considering heat exchange in storage tanks. The energy relationship is adjusted using a heat loss correction factor, and the gas state can be described using an adiabatic equation, such as equation (3):

$$QW^m = Q_0 W_0^m + D\left(R - R_{env}\right) \tag{3}$$

Among them:

- $Q$ and $W$ – the pressure and volume of gas in the gas storage tank
- $Q_0$ – the pressure in the initial state
- $m$ – the gas compression polynomial index
- $D$ – the system heat exchange parameters

- $R$ and $R_{env}$ – the current and ambient temperature.

In the energy storage mathematical model, energy storage efficiency is significantly affected by ambient temperature and pressure. High temperature will increase heat loss and reduce energy storage efficiency, while high pressure will help increase gas density and enhance energy storage capacity. Combining the non-ideal gas equation with the laws of thermodynamics, the model needs to introduce temperature and pressure correction terms to more accurately reflect the actual working conditions and improve the system energy utilisation and FM response accuracy.

When storing gas, gas compression causes pressure to rise, affecting energy storage efficiency, and sudden changes in pressure increase energy loss or safety risks. Therefore, it is critical to develop an energy storage strategy that balances pressure, temperature, and efficiency. When dynamically modelling an adiabatic CAES system (Xu et al., 2022), in addition to considering the gas state equation, the interaction between the energy in the gas tank and the external work must also be considered. According to the first law of thermodynamics, the change in air specific enthalpy during the energy storage stage is related to the total power $Q_{store}$ of the system, as shown in equation (4):

$$\frac{d}{dt}(ng) = Q_{store} - \gamma n d_w \left(R - R_{env}\right) \tag{4}$$

Among them:

- $n$ – the gas mass in the gas tank;
- $d_w$ – the specific heat capacity at constant volume;
- $R_{env}$ –the ambient temperature;
- $\gamma$ –the heat loss of the system.

Equation (4) combines heat loss to accurately describe the change in gas-specific enthalpy during energy storage and reflects the actual state of the gas tank. Real-time monitoring of the pressure and temperature of the gas tank and coordination with intelligent control algorithms can improve energy utilisation and enhance the stability and response speed of the power grid FM.

### *3.1.3 Energy release process modelling*

The energy release link is the key to converting high-pressure air into mechanical energy and outputting electrical energy. When the power grid needs to be supplemented, the high-pressure air releases energy through the expander to drive the turbine and generator. Although it is ideally regarded as a reverse compression process, the actual performance is affected by flow loss, heat exchange, and efficiency limitations and is lower than the theoretical value. Therefore, it is crucial to establish a precise mathematical model to describe the energy conversion characteristics during expansion to improve response and stability. To precisely describe the energy release process, this article describes the air expansion process by solving the generalised gas state equation and the thermodynamic energy conservation equation. Among them, the relationship between the expander output power $Q_{exp}$ is described as equation (5):

$$Q_{exp} = \dot{n}\left[\frac{d_q}{\beta-1}(R_1 - R_2) + D_{loss}(q_1W_1 - q_2W_2)\right] \tag{5}$$

Among them:

- $R_1$ and $R_2$ – the air temperature before and after expansion
- $q_1$ and $q_2$ – the pressure before and after expansion
- $W_1$ and $W_2$ – the corresponding volume
- $D_{loss}$ – the flow loss correction factor.

Equation (5) comprehensively considers thermodynamic characteristics and additional energy loss, making the energy release model more realistic. The heat change during expansion has a great impact on the system efficiency, and air cooling may cause water vapour condensation, affecting the operation of the expander. When modelling, it is necessary to consider the influence of specific enthalpy g and temperature change on energy release, which can be described by the energy balance equation, as shown in equation (6):

$$\frac{d}{dt}(ng) = Q_{exp,real} - \alpha n d_w (R - R_{env}) \tag{6}$$

Among them:

- $Q_{exp,real}$ – the actual output power of the expander;
- $\alpha$ –the air cooling loss coefficient.

Equation (6) shows that the specific enthalpy of air during energy release is affected by ambient temperature, expansion efficiency, and flow loss. Combined with the grid demand, the power and flow are dynamically adjusted so that the adiabatic electromagnetic CAES system can maintain efficient response and power under different loads, thereby enhancing the stability of the grid.

The ideal gas state equation assumes that there is no force between molecules and the molecular volume can be ignored, and is applicable to high temperature and low pressure conditions. However, the non-ideal gas equation takes into account the molecular volume and interaction force, and is closer to actual working conditions, especially showing significant differences under high pressure and low temperature. It can more accurately describe the gas behaviour in the energy storage system and improve the model accuracy and system control effect.

During the operation of the adiabatic electromagnetic compressed air energy storage system, the energy loss mechanism is complex and diverse. In the compression stage, the temperature rise caused by air compression is one of the main factors leading to energy loss. Although adiabatic compression is used to reduce heat loss, in the actual process, due to material heat conduction, friction and incomplete adiabatic conditions, part of the compression work will still be converted into heat energy and lost to the environment, resulting in energy loss. In the energy storage stage, the thermal insulation performance of the gas storage tank directly affects the energy retention efficiency. If the performance of the thermal insulation layer is not good, the high-pressure air in the gas storage tank will exchange heat with the external environment, resulting in a decrease in internal energy and a decrease in energy storage efficiency. In the process of energy release, the efficiency of the expander's work also affects the energy conversion. In the actual expansion process, due to flow loss, heat exchange and mechanical friction, the output work of the expander is often lower than the theoretical value, resulting in energy loss. In addition, the connecting pipes, valves, etc., between the various components of the system will also produce pressure drops due to fluid resistance, further increasing energy loss. Therefore, to optimise the adiabatic electromagnetic compressed air energy storage system, it is necessary to start from many aspects such as improving the compression and expansion efficiency, improving the thermal insulation performance of the gas storage tank, and reducing fluid resistance to reduce energy loss and improve the overall energy efficiency of the system.

### *3.1.4 Relationship modelling of grid frequency fluctuations*

Due to the random nature of grid load and renewable energy generation, the system requires dynamic adjustment of energy release rates to maintain grid frequency, which can be described by the power balance equation (Gulzar et al., 2022; Ortega and Milano, 2020). In adiabatic electromagnetic CAES systems, output power must be adjusted in real-time to compensate for frequency imbalance. This study employs a dynamic adjustment factor that considers inertia effects and response lag, with FD changes modelled using a second-order differential equation (Zhang et al., 2022a, 2024b), as shown in equation (7):

$$N\frac{d^2\Delta h}{dt^2}+C\frac{d\Delta h}{dt}+L_h\Delta h=\Delta Q_{load}-\Delta Q_{gen}+Q_{reg} \tag{7}$$

Among them:

- $N$ – the system inertia
- $C$ – the damping coefficient.

Equation (7) shows that the adiabatic electromagnetic CAES system needs to adjust the energy release power according to the grid FD to quickly respond to disturbances and maintain grid stability. To optimise the FM effect, the energy release mode is adjusted in combination with the real-time measurement results of the FD. By applying PID control, grid frequency changes are responded to flexibly to avoid excessive or delayed response. In a grid with a high proportion of new energy, it can cooperate with other energy storage means to enhance the overall FM capability.

## *3.2 Energy storage and release optimisation*

### *3.2.1 Real-time control framework design*

To quickly respond to grid frequency fluctuations, it is necessary to build an efficient real-time control framework to dynamically adapt to grid needs. The framework contains four parts: data acquisition, processing, decision algorithm, and execution. Data acquisition monitors grid frequency h and load fluctuations in real-time, and transmits information through high-speed sensors and transmission protocols. The processing unit analyses grid data, identifies frequency offset characteristics, and calculates the adjustment power in combination with the prediction model. The decision algorithm adopts nonlinear optimal control, comprehensively considers system inertia, response lag, and maximum energy release rate, and formulates the optimal energy release strategy. In this process, to meet the best FM effect, the energy release power of the adiabatic electromagnetic CAES system needs to follow the dynamic optimisation equation and consider relevant constraints. Its constraint equation is shown in equation (8):

$$\int_0^R \left( \kappa_1 (\Delta h)^2 + \kappa_2 \left( \frac{dQ_{reg}}{dt} \right)^2 \right) dtQ, \quad \text{s.t. } 0 \le Q_{reg} \le Q_{\max} \tag{8}$$

Among them:

- $\kappa_1$ and $\kappa_2$ – the adjusted weight coefficient, controlling the influence of FD and energy release power change rate
- $Q_{\max}$ –the maximum energy release power of the system.

The actuator adjusts the operating parameters such as the expander opening and the compressor start-stop strategy, in the adiabatic electromagnetic CAES system according to the decision algorithm signal. Fuzzy control and adaptive neural network technology are applied to make the adiabatic electromagnetic CAES system precisely adapt to the dynamic needs of the power grid. In the new energy high penetration power grid, this framework can cooperate with other energy storage technologies to achieve more precise and stable FM.

### *3.2.2 Storage and release optimisation*

The traditional adiabatic compression model is difficult to accurately describe heat transfer. Therefore, this article adopts an improved thermodynamic model, adds heat conduction terms to the adiabatic equation, considers the heat exchange between the system and the environment, and establishes the differential control equation, as shown in equation (9):

$$\frac{d}{dt}\left(QW^{\beta}\right) + lX\left(R - R_{env}\right) = 0 \tag{9}$$

Among them:

- $l$ –the heat conduction coefficient
- $X$ – the total surface area of gas in contact with the container.

By solving the parameters of equation (9), the optimal pressure and temperature change trajectory of the energy storage process can be obtained to guide the operation of the compressor. To reduce the energy loss in compression, multi-stage compression and intermediate cooling technology are adopted. By adding an intermediate cooler between each compression stage, the temperature of the air in the gradual compression process can be effectively reduced; the irreversible loss can be reduced; and the efficiency can be improved. When the energy is released, the adiabatic electromagnetic CAES system needs to transmit power to the grid quickly and stably, and the expander needs to be dynamically adjusted. To this end, this article applies the expansion loss term in the improved expansion process modelling to more precisely describe the efficiency loss. The calculation of the actual expansion power is shown in equation (10):

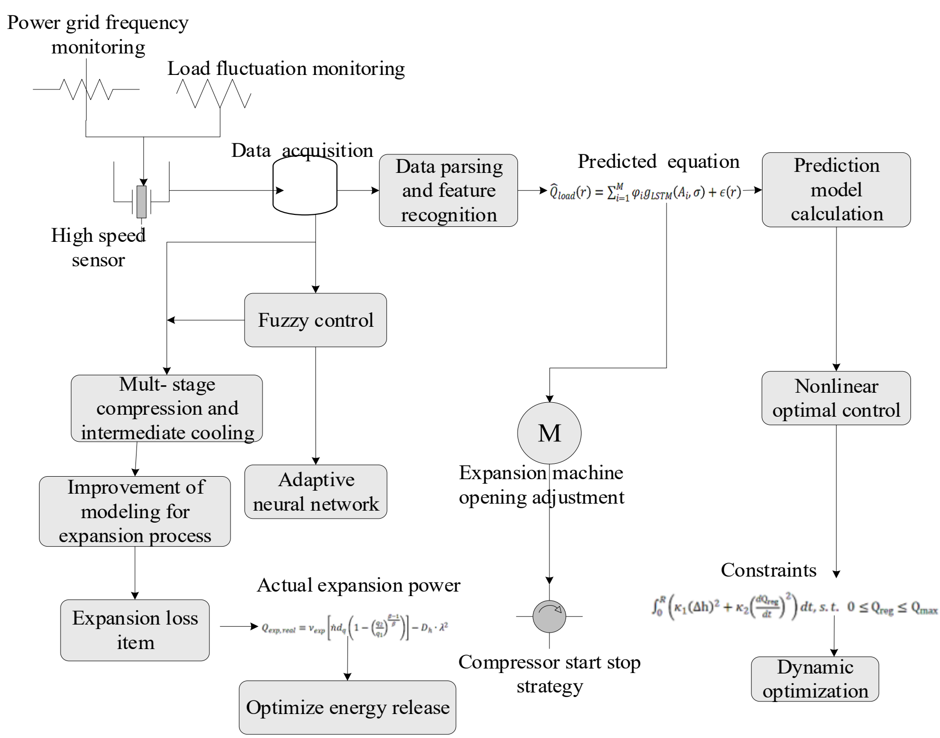
$$Q_{exp,real} = v_{exp}\left[\dot{n}d_q\left(1-\left(\frac{q_2}{q_1}\right)^{\frac{\beta-1}{\beta}}\right)\right]-D_h\cdot\lambda^2 \tag{10}$$

Among them:

- $v_{exp}$ –the expansion efficiency;
- $D_h$ –the friction loss coefficient;
- $q_1$ and $q_2$ – the state variables at the beginning and end
- $\lambda^2$ –the expander speed.

Adjusting $\lambda^2$ and $q_2$ can optimise the expansion process, make it better adapt to the change of grid load, and speed up the system response. The control strategy is adjusted in real-time according to the grid FD $\Delta h$ to ensure the stability of the grid. The implementation process of real-time control and adjustment of energy storage is shown in Figure 2.

**Figure 2** Implementation process of real-time control and adjustment of energy storage




From Figure 2, the data analysis and feature recognition module extracts key information from real-time monitoring data, including macro indicators such as grid frequency, voltage, power output, and micro data within the system. The processed data is input into the prediction model to predict future FDs. The fuzzy control module adjusts the compressor and expander states according to the prediction results to ensure the system's stable operation under different loads. Multi-stage compression and intermediate cooling technology are used to reduce energy loss in the compression process and improve efficiency. At the same time, the improved expansion process modelling applies expansion loss terms to precisely describe efficiency losses and dynamically adjust the expander speed to adapt to grid load changes.

### *3.2.3 Optimising the output curve of energy storage devices to match grid demand*

To enhance the adaptability of the adiabatic electromagnetic CAES system in grid FM, the energy storage device scheduling optimisation method based on load prediction is used (Zheng et al., 2022). The core is to build a precise load prediction model to guide the adjustment of the optimal output curve of energy storage devices. The improved LSTM model is utilised in combination with the wavelet transform for load prediction. The historical load data is first decomposed at multiple scales through wavelet transformation to remove high-frequency noise, and then input into LSTM for deep learning prediction (Zhang et al., 2022b). The prediction equation is shown in equation (11):

$$\hat{Q}_{load}(r) = \sum_{i=1}^{M} \varphi_i g_{LSTM}\left(A_i, \sigma\right) + \varepsilon(r) \tag{11}$$

Among them:

- $\hat{Q}_{load}(r)$ –the predicted load at time $r$
- $g_{LSTM}$ –the nonlinear mapping of LSTM
- $\varphi_i$ –the weights of each component after wavelet decomposition
- $\varepsilon(r)$ –the prediction error term.

LSTM is combined with the wavelet transform to decompose historical load data through wavelet, extract multi-scale features and remove high-frequency noise to improve data quality; then each scale component is input into the LSTM model for deep learning prediction. This method gives full play to the advantages of the wavelet transform in time-frequency analysis and the powerful learning ability of LSTM for sequence data, significantly improving the load prediction accuracy and stability, and provides a reliable basis for energy storage scheduling optimisation.

Based on the prediction results, a day is divided into multiple periods, and charging and discharging strategies are formulated for each period. During the low period at night, the energy storage device increases energy storage to reduce the wind and solar power abandonment rate; during the peak period during the day, the energy release is increased to reduce the FM pressure of thermal power units. To further enhance the stability of system operation, adaptive adjustment control is applied to the optimisation scheduling algorithm to enable the system to dynamically correct the charging and discharging plan. If the load prediction deviation is large, rolling optimisation is utilised to adjust the future charging and discharging power to reduce the scheduling error. At the same time, to avoid frequent start-stop losses of devices, the power change rate is limited by the constraint optimisation method to ensure the smoothness of the charging and discharging curve. This method can greatly enhance the FM accuracy of adiabatic electromagnetic CAES, reduce costs, improve grid stability, and promote the deep utilisation of new energy.

## 3.3 FM control strategy design

### 3.3.1 Frequency monitoring and deviation calculation

This study uses the signal processing method of STFT (Zhou et al., 2022) to extract the voltage and current waveform frequency in the power grid in real-time. STFT is a time-frequency analysis method that divides signals into short segments and performs Fourier transforms on each segment to capture the temporal variations of frequency components. By combining the frequency-domain analysis capabilities of the Fourier transform with the time-domain localisation characteristics of window functions, it effectively suppresses spectral leakage and enhances measurement accuracy. Assuming that the instantaneous signal of the power grid is a(r), its time-frequency representation can be obtained by STFT, as shown in equation (12):

$$A(r, \mu) = \int_{-\infty}^{\infty} a(\omega)\mu(\omega - r)e^{-j\mu\omega} d\omega \tag{12}$$

Among them, $\mu(\omega - r)$ is the sliding window function, and $\mu$ is the angular frequency.

Equation (12) method can filter out noise, precisely capture frequency changes in a short period of time, and improve the response capability of the adiabatic electromagnetic CAES system. This method can be used to obtain the current frequency $h(r)$ of the power grid in real-time, compare it with the target frequency $h_{target}$, and calculate the FD $\Delta h(r)$. During FM, in addition to the instantaneous value, the FD must also be calculated in combination with the historical trend to enhance control stability. Therefore, this article uses the exponentially weighted moving-average (EWMA) method to smooth the FD of real-time monitoring, as shown in equation (13):

$$\Delta h_{smooth}(r) = \varphi \Delta h(r) + (1 - \varphi)\Delta h_{smooth}(r - 1) \tag{13}$$

Among them, $\varphi$ –¸the smoothing coefficient, taking 0.1–0.3, to balance the response speed and noise resistance.

If $\Delta h_{smooth}(r)$ exceeds the threshold, the adiabatic electromagnetic CAES triggers the FM mechanism, quickly adjusting the energy release power of the compressed-air to compensate for the power grid frequency fluctuation.

STFT converts the time domain signal into time-frequency representation through a windowed Fourier transform, and extracts local frequency features through a sliding window; EWMA performs a weighted average on the frequency data output by STFT to highlight the influence of recent data. The frequency measurement accuracy and time domain response capability can be improved by combining parameter details such as window function selection, step size setting and smoothing coefficient adjustment, and enhancing the stability and dynamic performance of FM control.

STFT presents both advantages and limitations in power grid frequency analysis. Its strengths include:

1 detailed visualisation of signal frequency components over time, enabling effective monitoring of dynamic fluctuations

2 enhanced spectral leakage suppression through windowing techniques that improve measurement accuracy and perform well with non-stationary signals

3 real-time capture of frequency variations during grid frequency regulation, providing timely data for optimal control decisions.

Limitations involve:

1 temporal-frequency resolution constrained by window function selection and length, with fixed window lengths compromising both temporal precision and frequency resolution

2 high computational complexity that may hinder real-time processing when handling large datasets.

Therefore, practical implementation requires careful evaluation of these trade-offs based on specific application scenarios, enabling the selection of appropriate signal processing methods to achieve precise frequency analysis and effective grid regulation.

### *3.3.2 Rapid energy release strategy based on FD*

To ensure the stability of the power grid frequency, the adiabatic electromagnetic CAES system needs to design an efficient energy release strategy to quickly respond to the FD. This article proposes a rapid energy release strategy based on predictive control, which monitors the frequency change trend of the power grid in real-time and dynamically adjusts the energy release rate. In view of the random and sudden characteristics of power grid frequency fluctuations, a dynamic weighting factor $W(r)$ is added to the PID control to enhance the system's adaptability to different disturbance intensities, as shown in equation (14):

$$\Delta Q_{out}(r) = W(r)\left[ L_q \Delta h(r) + L_i \int_0^r \Delta h(\omega) e^{-\tau(r-\omega)} d\omega + L_d \frac{d\Delta h(r)}{dt} \right] \quad (14)$$

Among them:

- $\Delta Q_{out}$ –the output power change
- $W(r) = 1 + \varphi|\Delta h(r)|^m$ – the dynamic weighting factor
- $e^{-\tau(r-\omega)}$ – the memory attenuation factor.

The improvement of equation (14) is that when the FD $\Delta h(r)$ is small, the energy release is controlled by PID; when the FD $\Delta h(r)$ suddenly increases, the weighting factor $W(r)$ increases, prompting the system to release energy quickly and suppressing the frequency fluctuation from further increasing. After applying the dynamic weighting factor, the strategy can automatically adjust the response according to the FD amplitude, reduce overshoot, and make the energy release more stable.

### *3.3.3 Adaptive FM control algorithm*

In the FM control of adiabatic electromagnetic CAES, the traditional fixed parameter PID controller is difficult to adapt to the dynamic changes of grid load and the uncertainty of renewable energy generation. In this paper, an adaptive FM algorithm is used, and the PID control parameters are updated online by the recursive least squares method (RLS), so that the system can adjust the strategy in real time to achieve efficient and accurate FM. RLS collects data in real time and calculates the optimal parameters recursively, which can quickly adapt to changes in the frequency of the power grid, cope with uncertainty, improve response speed and stability, and ensure the frequency adjustment of the power grid. The control law is the PID standard form, as shown in equation (15):

$$o(r) = L_q e(r) + L_i \int_0^r e(\omega) d\omega + L_d \frac{de(r)}{dt} \tag{15}$$

Among them, $e(r) = h_{target}$ –the FD.

To improve the system's adaptability, the RLS parameter update mechanism is applied, and the update iteration equation is shown in equation (16):

$$\eta(r) = \eta(r-1) + Q(r)\phi(r)\left[e(r) - \phi^R(r)\eta(r-1)\right] \tag{16}$$

Among them:

- $\eta(r) = [L_q, L_i, L_d]^R$ – the PID parameter vector;
- $\phi(r)$ – the feature input;
- $Q(r)$ –the covariance matrix.

RLS dynamically estimates system parameters by updating data online in real time, thereby adjusting the proportional, integral and differential coefficients of the PID controller. Its core principle is to optimise parameter estimation by minimising the sum of squared errors, and it has the advantages of fast convergence speed, high accuracy and strong adaptability. In complex and changeable power grid frequency regulation scenarios, the RLS algorithm can quickly track system dynamic changes, improve the robustness and adaptability of the control system, and is suitable for parameter identification and control optimisation in nonlinear and time-varying systems.

## 4 Grid FM experiment

### *4.1 Experimental design*

To verify the effectiveness of the adiabatic electromagnetic CAES system in grid FM, this study builds an experimental platform including an adiabatic electromagnetic CAES system model and a grid simulation environment. The adiabatic electromagnetic CAES system consists of a high-efficiency gas compressor, an optimised gas storage tank, a high-efficiency energy release device, and a real-time frequency monitoring system. The gas compressor compresses and cools the air to reduce energy loss; the salt cavern is utilised as an energy storage medium to ensure high energy density and low heat loss; the energy release device converts high-pressure air energy into electrical energy through an expander. The frequency monitoring system monitors and responds quickly to FDs in real-time and triggers adjustment measures. In the experimental design, a variety of test conditions are set for the FM performance of the adiabatic electromagnetic CAES system. The FD at different time points is simulated, and the change of grid load from 40% to 150% is simulated. Random disturbance factors are applied to simulate emergencies. The experiment lasts for one month, and multiple tests are conducted every day. Before each experiment, the grid state is initialised to 50 Hz, and then the test is started. Key data such as system response time and grid FD are recorded to evaluate its performance. The basic environment of the simulation platform is described in Table 1.

**Table 1** Basic environment table of the simulation platform

| *Serial number* | *Parameter name* | *Parameter value/description* | *Specific parameters* |
|---|---|---|---|
| 1 | System model | Accurate simulation | Accuracy error < 5% |
| 2 | High-efficiency gas compressor | Compression ratio > 5:1 | Output pressure 30 MPa |
| 3 | Cooler | Drop to ambient temperature | Outlet air temperature ≤ 40°C |
| 4 | Optimised design of gas storage tank | Salt cave as a storage medium | Energy density 50 kWh/m: |
| 5 | High-efficiency energy release device | Expander | Efficiency > 85% |
| 7 | Power grid simulation environment | Multiple load conditions and disturbances | Load fluctuation range 40–150% |

In the data collection stage, to ensure the accuracy and reliability of the experiment, a high-frequency sensor network is deployed in the power grid simulation platform to capture key parameters in real-time. These parameters include macro indicators such as grid frequency, voltage, and power, as well as micro data such as compressor efficiency, gas tank status, and energy release device output inside the adiabatic electromagnetic CAES system. This article uses high-precision frequency sensors to monitor grid frequency, voltage transformers to record voltage, and electric energy meters to obtain power output. For the system, the compressor efficiency is calculated by pressure and temperature sensors; the high-sensitivity sensor monitors the gas tank status; the power analyser measures the output of the energy release device. All data are collected in real-time via a high-speed transmission protocol and stored in a centralised database for subsequent analysis. In the experiment, thermal power units, battery energy storage systems, flywheel energy storage, and wind turbines are selected as comparison methods to evaluate the performance of this method and these four methods in grid FM. All experiments are carried out under the same frequency fluctuations and low to high load changes to ensure comparable results. The experiment first compares the frequency changes of the power grid under different signal processing amplifications, and then tests the FM control deviation, FM accuracy, response time, and FM effect under different loads. The response speed and accuracy of each system under different loads are monitored and recorded in real-time. The basic situation of data collection is described in Table 2.

**Table 2** Basic situation table of data collection

| *Serial number* | *Parameter name* | *Data source/device* | *Measuring range* | *Accuracy/error* |
|---|---|---|---|---|
| 1 | Grid frequency | High-precision frequency sensor | 49–51 Hz | ±0.001 Hz |
| 2 | Voltage level | Voltage transformer | 0–1,000 V | ±0.1% |
| 3 | Power output | Precision energy meter | 0–10 MW | ±0.2% |
| 4 | Compressor efficiency | Pressure and temperature sensors | Pressure: 0–30 MPa | Pressure: ±0.5%, temperature: ±0.1°C |
| 5 | Gas tank pressure | Pressure sensor | 0–30 MPa | ±0.5% |
| 6 | Tank temperature | Temperature sensor | –20–100°C | ±0.1°C |

## *4.2 Experimental results*

### *4.2.1 Grid frequency change*

This article uses the collected grid data to show the changes in grid frequency under different signal processing methods. These grid data jointly optimise the system operation strategy and verify its ability to maintain grid frequency stability under different loads. The specific changes in grid frequency are shown in Figure 3.

**Figure 3** Grid frequency change diagram (see online version for colours)

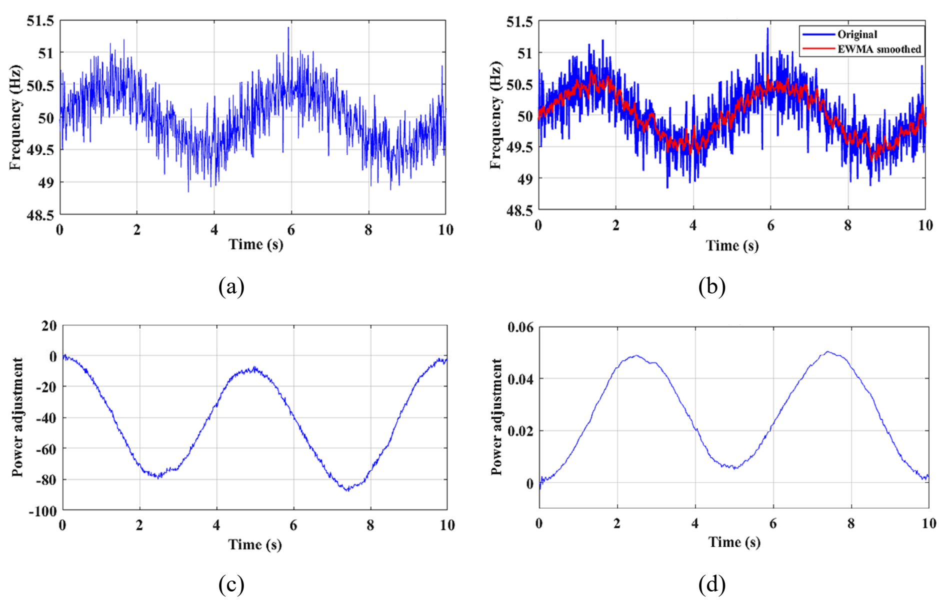


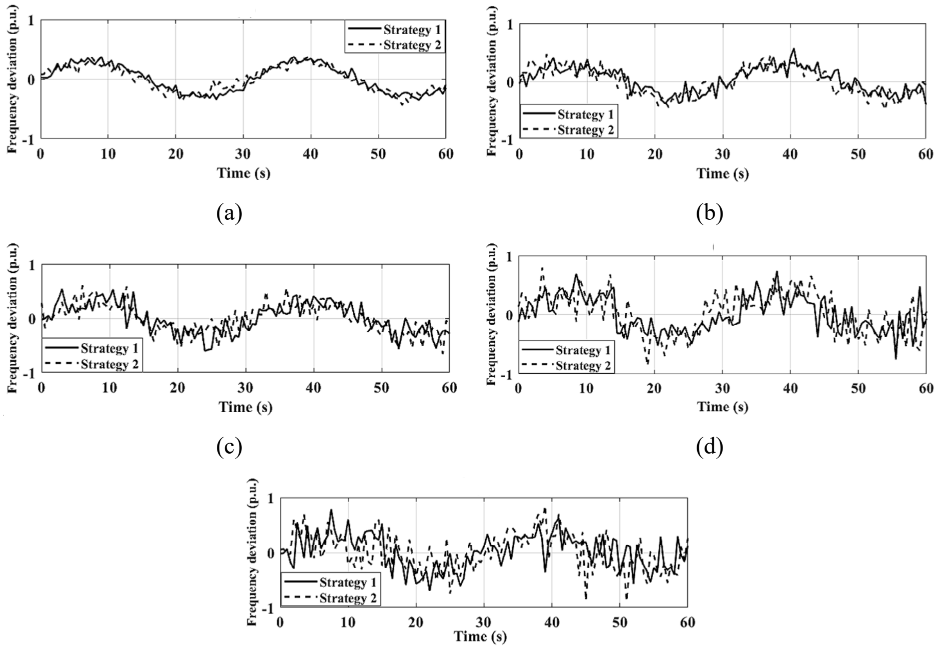
Figure 3 (a) shows the original grid frequency change; Figure 3(b) shows the EWMA smoothed frequency; Figure 3(c) shows the PID frequency control; Figure 3(d) shows the adaptive PID frequency control. The grid frequency change diagram contains four sub-diagrams, which fully show the process and results of each stage of frequency regulation. Figure 3(a) is the original grid frequency signal. Due to external interference, the frequency basically fluctuates between 49 Hz and 51.5 Hz, accompanied by random high-frequency oscillations. This fluctuation is mainly caused by changes in grid load and the instability of renewable energy such as wind power and photovoltaics. Figure 3(b) is the signal processed by EWMA technology. The red curve appears to be more stable than the original frequency signal, effectively suppressing short-term fluctuations. Figure 3(c) shows the power adjustment under the PID regulation strategy. The PID control adjusts the power according to the FD to achieve dynamic energy release. The periodic changes of power adjustment in the figure are similar to the grid frequency fluctuations, showing the good response of PID control to FD. Figure 3(d) is the power adjustment curve of adaptive PID adjustment. Compared with traditional PID, the adaptive PID uses RLS dynamic parameter adjustment, and the output curve is smoother and can quickly follow the frequency change. EWMA performs well in smoothing noise, while adaptive PID has more advantages in fast frequency adjustment, providing strong support for adiabatic electromagnetic CAES FM.

### *4.2.2 FM control deviation*

Grid FM control deviation is the key to measuring the effect of adiabatic electromagnetic CAES FM, which reflects the system's accuracy and efficiency in restoring the grid frequency. Analysing this deviation can optimise the FM strategy and enhance the system's stability and adaptability. To this end, this article sets out two strategies, namely strategy 1: the dead zone of energy storage FM is less than 60% of the traditional unit; strategy 2: the dead zone of energy storage FM is less than the traditional unit. First, the experimental FM control deviations under five methods are tested, as illustrated in Figure 4.

Figure 4(a) is the FM control deviation of the power grid under this article's method; Figure 4(b) is the FM of the thermal power unit; Figure 4(c) is the battery energy storage system; Figure 4(d) is the flywheel energy storage; Figure 4(e) is the wind turbine. As shown in Figures 4(a), 4(b), 4(c), 4(d) and 4(e), within 0 to 60 seconds, the FD of strategies 1 and 2 under the proposed method fluctuates within the range of about –0.25 p.u. to 0.25 p.u.; the FD of the thermal power unit FM fluctuates within the range of about –0.45 p.u. to 0.55 p.u.; the FD of the battery energy storage system fluctuates within the range of about –0.75 p.u. to 0.75 p.u.; the FD of the flywheel energy storage fluctuates within the range of about –0.8 p.u. to 0.8 p.u.; the FD of the wind turbine fluctuates within the range of about –0.9 p.u. to 0.9 p.u. It can be learned that the FM control deviation of the proposed method is the smallest, which is due to its optimised energy storage and release process, and it can quickly respond to changes in grid frequency. Other methods such as thermal power units, battery energy storage systems, flywheel energy storage, and wind turbines are limited by their respective characteristics and cannot achieve the same accuracy and speed. Therefore, in the power grid environment with high penetration of new energy, the adiabatic electromagnetic CAES system provides a more stable and efficient solution.

**Figure 4** Experimental FM control deviation

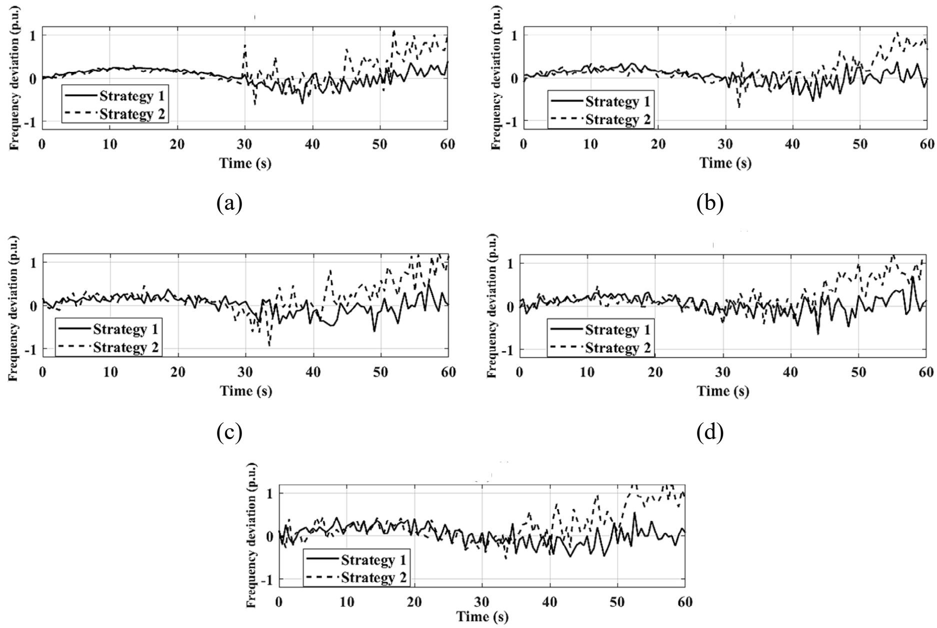



(a) (b) (c) (d) (e)

Subsequently, this article adds a 2-minute random disturbance to the power grid and obtains the FM control deviation under five methods, as displayed in Figure 5.

Figure 5(a) shows the FM control deviation of the power grid under the proposed method; Figure 5(b) shows the FM of thermal power units; Figure 5(c) shows the battery energy storage system; Figure 5(d) is the flywheel energy storage; Figure 5(e) is the wind turbine. Figure 5 compares the frequency control deviation of five FM methods under 2 minutes of random disturbances. Figure 5(a) shows that the FD of strategy 1 and strategy 2 are both small. During the disturbance period after 30 seconds, the FD of strategy 1 fluctuates within [–0.45, 0.5] p.u., and that of strategy 2 fluctuates within [–0.6.5, 1.05] p.u., indicating that the proposed method has good robustness. Figure 5(b) shows that the FD of thermal power units is large during the disturbance. The fluctuation range of strategy 1 and strategy 2 in the first 30 seconds is approximately [–0.35, 0.35] p.u. and [–0.2, 0.4] p.u., respectively. The deviation increases significantly after 30 seconds. Figure 5(c) shows that the FD of the battery energy storage system is also large during the disturbance, and strategy 2 fluctuates significantly. Figure 5(d) depicts that the FD of the flywheel energy storage system also increases. Figure 5(e) shows that the FD of the wind turbine is large during the disturbance, and its fluctuation is violent. Overall, with the increase in time, the FD of each method gradually increases, especially within 30 seconds after the disturbance begins. Among them, the method in this article performs better and has the smallest FD, which is due to its efficient energy storage and rapid response capability. However, due to physical characteristics and technical limitations, other methods have large FDs when facing random disturbances.

**Figure 5** FM control deviation after adding random disturbances



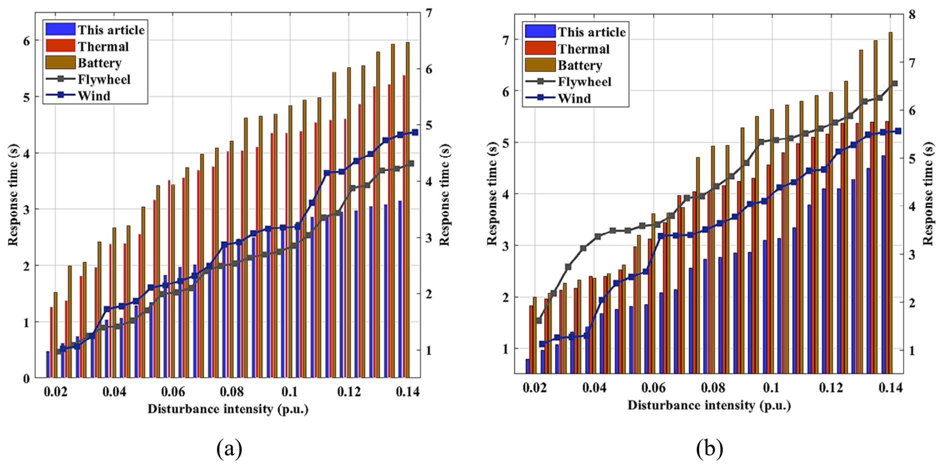

(a) (b) (c) (d) (e)

## *4.2.3 Response time*

Response time is the key to evaluating the efficiency of FM, which reflects the system's ability to respond quickly to changes in grid frequency. A shorter response time helps to quickly compensate for FD and improve the power grid's stability and reliability in emergencies. This article uses random disturbance intensity as the evaluation criterion to test the response time of two strategies under five methods, as illustrated in Figure 6.

Figure 6(a) depicts the response time of the first strategy, and Figure 6(b) depicts the response time of the second strategy. Under the first strategy, when the disturbance intensity is 0.02 p.u., the response time of this method is 0.477 seconds, which is better than 1.270 seconds for thermal power units, 1.521 seconds for battery energy storage systems, 0.969 seconds for flywheel energy storage, and 1.021 seconds for wind turbines. When the disturbance intensity increases to 0.14 p.u., the response time of this method is 3.135 seconds, while the other methods are 5.383 seconds, 5.959 seconds, 4.308 seconds, and 4.863 seconds, respectively. Figure 6(b) shows that under the second strategy, the proposed method increases from 0.790 seconds to 4.739 seconds, while the other methods increase more, with the battery energy storage system and flywheel energy storage system reaching 7.136 seconds and 6.550 seconds, respectively, when the disturbance intensity increases to 0.14 p.u. These data show that the adiabatic electromagnetic CAES method in this article responds quickly under various disturbance intensities, showing its excellent adaptability and rapid response capabilities. This is due to the fact that the technology combines efficient energy storage with rapid energy release, and can quickly adjust power to cope with grid fluctuations. Compared with other methods, this method has a smaller increase in response time when the disturbance is enhanced, which proves the superiority of its FM performance. This conclusion is crucial to the optimisation of grid stability and provides strong data support for subsequent research. Through the combination of efficient energy storage and rapid release technology, this method shows great potential in grid stability maintenance.

**Figure 6** Response time comparison (see online version for colours)




### *4.2.4 FM accuracy*

FM accuracy reflects the system's ability to stabilise the grid frequency, and high accuracy can more accurately maintain grid stability. Experimental testing of FM accuracy can evaluate the effectiveness and reliability of the technology. Optimising FM accuracy can reduce FD, improve power system efficiency and stability, and ensure power supply quality. To this end, this article takes FD as the evaluation standard and first tests the FM accuracy under different disturbance intensities under strategy 1, as displayed in Table 3.

According to the data in Table 3, under a disturbance of 0.02 p.u., the FD of the adiabatic electromagnetic CAES technology in this article is only ±0.011 p.u., which is better than ±0.059 p.u. of thermal power units, ±0.062 p.u. of battery energy storage, ±0.042 p.u. of flywheel energy storage, and ±0.042 p.u. of wind power generation. When the disturbance increases to 0.14 p.u., the FD of the method in this article is ±0.057 p.u., while the accuracy of other methods drops significantly, with deviations of ±0.138 p.u., ±0.150 p.u., ±0.103 p.u., and ±0.091 p.u., respectively. This shows that regardless of the size of the disturbance, the technology in this article can maintain the grid frequency more stably, demonstrating its excellent adaptability and reliability. This is due to the fact that the technology combines efficient energy storage with a fast release mechanism, can quickly respond to load and renewable energy fluctuations, and effectively reduces FDs. The data also shows that although the FM accuracy of all methods decreases as the disturbance increases, the decrease of this method is smaller, which once again confirms its advantage. This conclusion verifies the great potential of this technology in improving the FM accuracy of power systems and provides strong support for the optimisation of power grid stability.

**Table 3** Accuracy under strategy 1

| *Disturbance intensity (±p.u.)* | *This article* | *Thermal power unit* | *Battery energy storage system* | *Flywheel energy storage* | *Wind turbine* |
|---|---|---|---|---|---|
| 0.02 | ±0.011 | ±0.059 | ±0.062 | ±0.042 | ±0.042 |
| 0.03 | ±0.017 | ±0.071 | ±0.063 | ±0.042 | ±0.044 |
| 0.04 | ±0.020 | ±0.074 | ±0.089 | ±0.043 | ±0.044 |
| 0.05 | ±0.024 | ±0.079 | ±0.093 | ±0.045 | ±0.052 |
| 0.06 | ±0.028 | ±0.085 | ±0.098 | ±0.047 | ±0.054 |
| 0.07 | ±0.035 | ±0.098 | ±0.098 | ±0.059 | ±0.057 |
| 0.08 | ±0.038 | ±0.098 | ±0.112 | ±0.066 | ±0.061 |
| 0.09 | ±0.038 | ±0.118 | ±0.135 | ±0.069 | ±0.061 |
| 0.1 | ±0.041 | ±0.123 | ±0.140 | ±0.071 | ±0.074 |
| 0.11 | ±0.043 | ±0.123 | ±0.147 | ±0.080 | ±0.076 |
| 0.12 | ±0.044 | ±0.130 | ±0.149 | ±0.084 | ±0.081 |
| 0.13 | ±0.046 | ±0.131 | ±0.149 | ±0.098 | ±0.090 |
| 0.14 | ±0.057 | ±0.138 | ±0.150 | ±0.103 | ±0.091 |

**Table 4** FM accuracy under strategy 2

| *Disturbance intensity (±p.u.)* | *This article* | *Thermal power unit* | *Battery energy storage system* | *Flywheel energy storage* | *Wind turbine* |
|---|---|---|---|---|---|
| 0.02 | ±0.031 | ±0.086 | ±0.102 | ±0.066 | ±0.056 |
| 0.03 | ±0.035 | ±0.096 | ±0.112 | ±0.070 | ±0.056 |
| 0.04 | ±0.037 | ±0.119 | ±0.112 | ±0.076 | ±0.061 |
| 0.05 | ±0.044 | ±0.127 | ±0.125 | ±0.083 | ±0.084 |
| 0.06 | ±0.047 | ±0.145 | ±0.129 | ±0.087 | ±0.090 |
| 0.07 | ±0.059 | ±0.148 | ±0.140 | ±0.093 | ±0.101 |
| 0.08 | ±0.063 | ±0.156 | ±0.147 | ±0.100 | ±0.103 |
| 0.09 | ±0.068 | ±0.158 | ±0.149 | ±0.111 | ±0.111 |
| 0.1 | ±0.069 | ±0.158 | ±0.150 | ±0.125 | ±0.120 |
| 0.11 | ±0.072 | ±0.162 | ±0.159 | ±0.134 | ±0.124 |
| 0.12 | ±0.074 | ±0.162 | ±0.162 | ±0.136 | ±0.129 |
| 0.13 | ±0.088 | ±0.163 | ±0.174 | ±0.143 | ±0.132 |
| 0.14 | ±0.090 | ±0.167 | ±0.180 | ±0.149 | ±0.136 |

Afterwards, for strategy 2, this article also tests the frequency accuracy under several different methods, as displayed in Table 4.

The data in Table 4 shows that when the disturbance intensity is 0.02 p.u., the FD of the adiabatic electromagnetic CAES technology in this article is ±0.031 p.u., which is significantly better than ±0.086 p.u. of thermal power units, ±0.102 p.u. of battery energy storage, ±0.066 p.u. of flywheel energy storage, and ±0.056 p.u. of wind power generation. When the disturbance intensity increases to 0.14 p.u., the FD of the method in this article increases to ±0.090 p.u., while the deviations of other methods increase significantly, such as the thermal power unit increasing to ±0.167 p.u. and the battery energy storage increasing to ±0.180 p.u. This shows that regardless of the size of the disturbance, the technology in this article can more precisely maintain the stability of the grid frequency, highlighting its excellent adaptability and reliability. This is because the efficient energy storage and rapid release mechanism of the method in this article enables the grid to quickly adjust when facing load changes or fluctuations in renewable energy, effectively reducing FDs.

### *4.2.5 FM Effect under different load conditions*

By testing the FM effect under different loads, the adaptability and reliability of the technology are verified to ensure the stability of the grid frequency. To this end, this article first tests the FM effect under different load conditions for strategy 1, as displayed in Figure 7.

**Figure 7** FM effect under strategy 1 (see online version for colours)

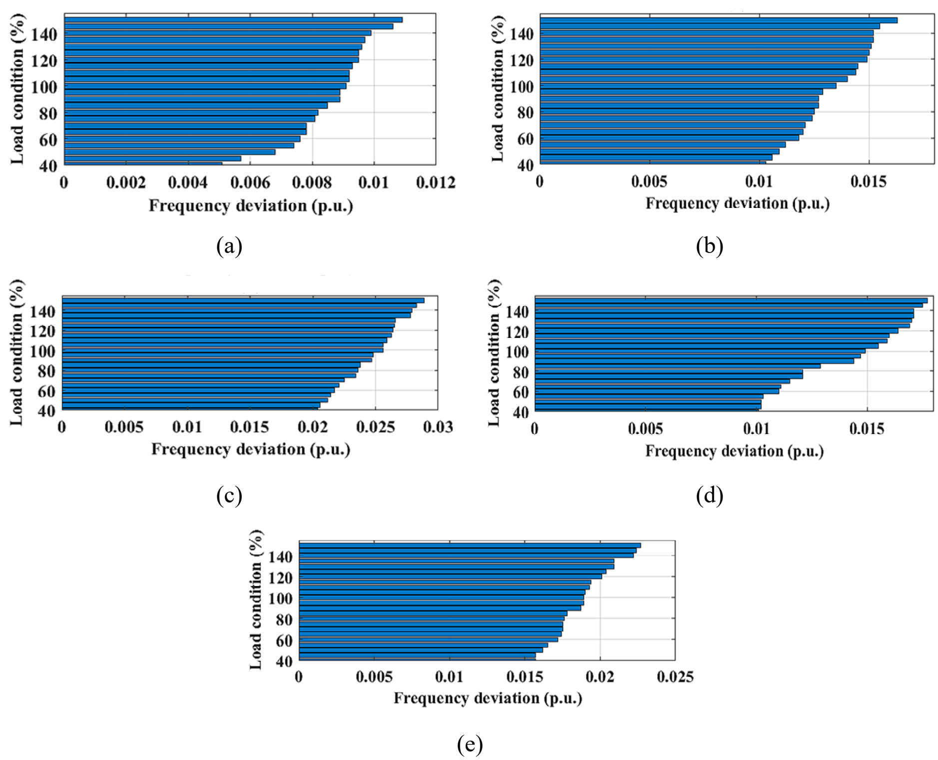



Figure 7(a) shows the FM effect of the method in this article; Figure 7(b) shows the FM of the thermal power unit; Figure 7(c) shows the battery energy storage system; Figure 7(d) shows the flywheel energy storage; Figure 7(e) shows the wind turbine. As shown in Figures 7(a), 7(b), 7(c), 7(d) and 7(e), under strategy 1, the adiabatic electromagnetic CAES technology in this article shows excellent FM performance under various loads. Taking 40% load as an example, the FD of this method is extremely low, only 0.0051 p.u., which is much lower than 0.0103 p.u. of thermal power units, 0.0204 p.u. of battery energy storage, 0.0101 p.u. of flywheel energy storage, and 0.0157 p.u. of wind turbines. At extremely high loads such as 150%, this method still performs well, with a FD of only 0.0109 p.u., while other methods reach 0.0163 p.u., 0.0289 p.u., 0.0177 p.u., and 0.0227 p.u., respectively. This shows that no matter how the load changes, the technology in this article can precisely maintain the stability of the grid frequency, highlighting its excellent adaptability and reliability. This technology combines efficient energy storage with rapid energy release, so it can quickly adjust in the face of load fluctuations and significantly reduce FD. As the load increases, although the FD of all methods increases, the increase of this method is significantly smaller. Under high load conditions, the FD of this method remains at a low level, further verifying its superiority.

Then, the FM effect under different load conditions is tested for strategy 2, as displayed in Figure 8.

**Figure 8** FM effect under strategy 2 (see online version for colours)

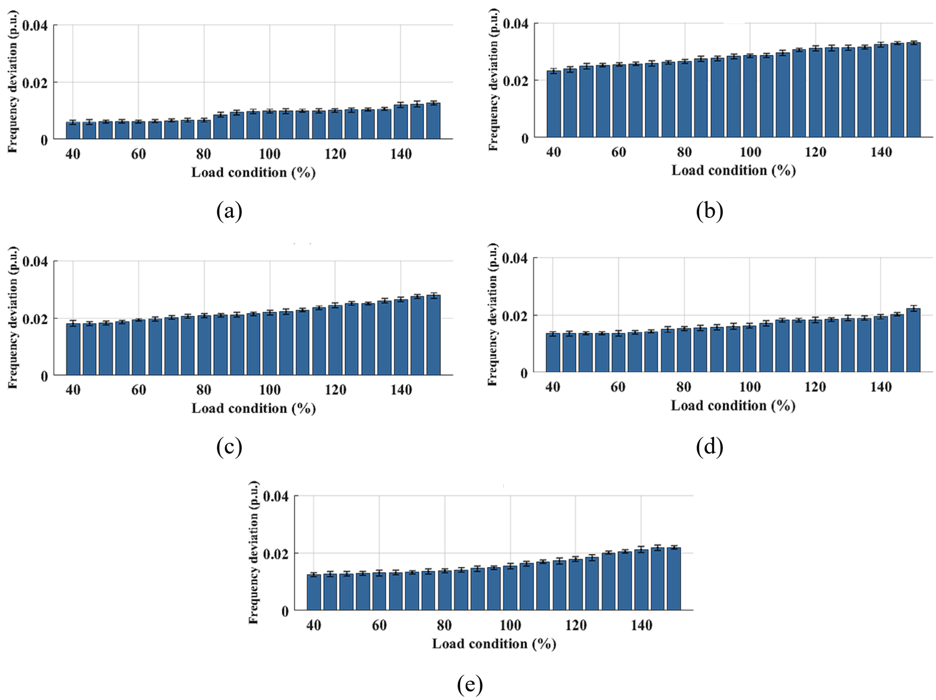



Figure 8(a) shows the FM effect of the proposed method; Figure 8(b) shows the FM of the thermal power unit; Figure 8(c) shows the battery energy storage system; Figure 8(d) shows the flywheel energy storage; Figure 8(e) shows the wind turbine. From Figures 8(a), 8(b), 8(c), 8(d) and 8(e), under strategy 2, the adiabatic electromagnetic CAES technology proposed in this article performs excellently and can effectively stabilise the grid frequency under various load conditions. At 40% load, the FD of the proposed method is only 0.0060 p.u., which is much lower than 0.0231 p.u. of the thermal power unit, 0.0181 p.u. of the battery energy storage, 0.0135 p.u. of the flywheel energy storage, and 0.0125 p.u. of the wind turbine. At extremely high loads such as 150%, the FD of the proposed method is only 0.0127 p.u., while the other four methods reach 0.0330 p.u., 0.0279 p.u., 0.0223 p.u., and 0.0218 p.u., respectively. This result shows that the adiabatic electromagnetic CAES technology proposed in this article can more precisely control the FD within a wide range of loads, highlighting its excellent adaptability and stability. This is due to the efficient energy storage and rapid release characteristics of the technology, which enable it to respond quickly to load changes and thus reduce frequency fluctuations.

When evaluating the application of compressed air energy storage (CAES) in grid frequency regulation, environmental factors significantly impact system performance. External conditions such as ambient temperature, humidity, and air pressure directly affect energy storage efficiency and stability. Temperature fluctuations alter the thermodynamic properties of compressed air: high temperatures reduce efficiency, increase energy consumption, and weaken thermal insulation; high humidity accelerates equipment corrosion and requires additional moisture management; air pressure variations influence storage density, energy capacity, and release efficiency. Therefore, when designing insulated electromagnetic CAES systems, comprehensive consideration of environmental factors is essential. Measures, including optimised tank insulation design, corrosion-resistant materials for high-humidity environments with regular maintenance, and pressure-adjusted compression strategies can mitigate adverse effects, ensuring stable and efficient system operation.

## 5 Conclusions

Research on the application of adiabatic electromagnetic CAES systems in grid frequency regulation demonstrates their significant advantages in enhancing grid stability. Studies confirm their outstanding performance in frequency regulation accuracy, response speed, and load adaptability. In grids with high renewable energy penetration, these systems effectively address the uncertainties and fluctuations of renewable energy sources, providing flexible and efficient FM support. Optimised control strategies further improve frequency regulation performance, ensuring reliable operation under complex grid conditions. Experiments reveal the immense potential of this energy storage system, offering a new high-efficiency solution for grid frequency regulation. Its characteristics of high-efficiency energy storage and rapid energy release enable swift adjustments during power fluctuations, maintaining stable grid frequencies.

This study has certain limitations, including that the energy conversion efficiency and cost control of the adiabatic electromagnetic CAES system are still facing challenges, the complex control strategy increases the difficulty of system design and maintenance, and the current research mainly focuses on frequency regulation performance, and the expansion of research on other grid service functions is still insufficient. Future research can focus on improving the energy conversion efficiency of adiabatic electromagnetic CAES systems, reducing costs, optimising intelligent control strategies to enhance adaptability and stability, and exploring their deep integration with renewable energy systems to achieve multi-energy complementary and coordinated operation, and promote their widespread application in grid frequency regulation and other auxiliary services.

## Declarations

This research is supported by the Technology Project of State Grid Jiangsu Electric Power Co., Ltd. (Project No. J2024202).

All authors declare that they have no conflicts of interest.

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