Energy Informatics

RESEARCH Open Access

Frequency stability of new energy power systems based on VSG adaptive energy storage coordinated control strategy

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Abstract

A self-adaptive energy storage coordination control strategy based on virtual synchronous machine technology was studied and designed to address the oscillation problem caused by new energy units. By simulating the characteristics of synchronous generators, the inertia level of the new energy power system was enhanced, and frequency stability optimization was achieved. This strategy is integrated with the frequency response model of the new energy power system to improve the system's frequency regulation capability and achieve more stable and efficient operation. From the results, the damping of the system increased, the oscillation frequency decreased after a duration of about 15 s, and the system stability improved by 76.09%. The proposed strategy based on virtual synchronous generator adaptive energy storage coordination control strategy was improved by 83.25%. In addition, the proposed strategy has improved stability indicators and system completion efficiency by 40.57% and 22.21% respectively, both of which are better than the comparative strategies. As a result, this strategy significantly enhances the frequency regulation capability of the system, which has a positive effect on achieving efficient operation of the new energy power system and maintaining the stability of the power system.

Keywords: VSG technology, Power system, Frequency, Coordinated control, Adaptive energy storage

Introduction

With the global energy structure transformation and the rapid reformation of new energy technologies, the large-scale grid connected operation of renewable energy sources like wind and solar energy has become an inevitable trend (Perez 2020). The new power system exerts a vital function in reducing carbon emissions and optimizing energy structure. However, due to its strong output volatility and difficulty in scheduling, it has brought unprecedented challenges to the frequency stability (Sun et al. 2019). The traditional frequency control mechanism based on inertial response is no longer fully adaptable to the regulatory needs of new energy power systems. Exploring frequency control strategies that are suitable for the characteristics of new energy has significant theoretical and practical significance (Sun et al. 2023). Although various frequency control methods have been proposed and applied to actual power grids, they often appear inadequate in the face of rapidly changing power grid environments. For example, traditional PI control methods may encounter response lag and insufficient stability when dealing with large-scale renewable energy integration. Meanwhile, although existing intelligent control methods have good adaptability, they still face challenges of high computational complexity and poor real-time performance in practical applications. In existing research, Virtual Synchronous Generator (VSG) technology is considered an active way to improve the dynamic stability of power systems after new energy grid connection due to its ability to simulate the inertia and damping characteristics (Chen et al. 2019). However, VSG still faces optimization issues in response speed and coordination performance in practical applications (Xiao et al. 2023). How to organically combine it with VSG technology to comprehensively improve the frequency stability of new energy power systems is still a current research difficulty.

Therefore, in order to develop a new frequency stability control strategy and improve the overall performance of the power grid, a VSG-based adaptive energy storage coordination control strategy is designed. Through in-depth analysis of the output characteristics and dynamic behavior of new energy, the fast and stable response of new energy power systems in the large-scale fluctuations can be achieved. It is hope to enhance frequency stability based on the adaptive adjustment ability of the enhanced system. The expected contribution of the research lies in the expectation that the implementation of this strategy can enhance the adaptability and stable operation ability of the power system to new energy grid connection, while also providing theoretical support and technical reference for frequency stability issues of similar systems.

The main impact of the study is that improving the frequency stability of the power grid can significantly improve its reliability and reduce the risk of large-scale power outages caused by frequency fluctuations; An improved frequency control strategy can enhance the economic benefits of the power grid and reduce operating costs through a more stable power supply. In addition, optimizing frequency control can also reduce power grid losses, thereby bringing certain environmental benefits and reducing carbon emissions.

The research has five parts. The first part summarizes the VSG technology and adaptive energy storage systems. The second part elaborates on the design principle and operating mechanism of an adaptive energy storage coordinated control strategy based on VSG, including mathematical modeling and simulation analysis of control algorithms. The third part is to verify the feasibility and effectiveness of the strategy in actual power systems by building corresponding experimental platforms and conducting system tests using various typical scenarios. The fourth part is a discussion. The last part is a summary.

Related work

Application status of VSG technology

In the field of frequency stability in new energy power systems, the VSG technology has received widespread attention. Its core advantage lies in simulating the traditional generators' inertia and damping characteristics, providing a potential solution for frequency instability caused by fluctuations in new energy sources. Many researchers have conducted in-depth discussions on this topic. Li et al. optimized the VSG's output impedance. The study first analyzed the dynamic performance under different control structures and determined the output impedance boundary that could suppress transient currents. Based on the Lyapunov stability theory, the output impedance boundary required to ensure electromechanical transient stability was further demonstrated. A control strategy was developed. The research results indicated that the proposed strategy was effective at both theoretical and experimental levels, providing a new solution for VSG in dealing with large interference stability issues (Li et al. 2022a). Goud et al. used machine learning to model the growth kinetics of undercooled metal alloys to address the limitation of traditional growth models due to simplified assumptions. The study utilized 910 data points. The R-2 cross validation score of the artificial neural network exceeded 0.89. The research results indicated that the trained algorithm could accurately predict the growth rate, showing good consistency with obtained data (Goud et al. 2022). Saffar et al. evaluated the impact of different current limiting strategies on the VSG's transient stability. The research results indicated that it reshaped the power angle curve by prioritizing the current vector angle, adjusting the d-axis and q-axis currents. Especially, it provided greater transient stability margin, which was longer critical clearing time, than other methods (Saffar et al. 2023). Xuan et al. conducted a spatially resolved study on the emission characteristics of polycyclic aromatic hydrocarbons in the nuclear and extranuclear regions of the M51a galaxy using a Spitzer IRS infrared spectrometer. The research results indicated that the nuclear region exhibited a strong correlation in the PAH intensity ratio. The extranuclear region showed signs of enhanced interstellar medium scattering. The hardness of the radiation field had a more significant impact on PAH emission than the abundance of metals. The metal abundance adjusted the PAH characteristics with the distance from the center of the galaxy (Xuan et al. 2022). Srivastava et al. compared the physiological effects of Roux-en-Y gastric bypass surgery and vertical sleeve gastrectomy on the liver of an obese mouse model. The research results indicated that both of them reduced liver weight, lowered cholesterol and triglyceride levels, and improved the activity score and fibrosis staging of non-alcoholic fatty liver disease. Therefore, gastric bypass surgery was more effective in improving liver physiology and function than vertical sleeve gastrectomy (Srivastava et al. 2022).

Improvements related to VSG technology

Many researchers have attempted to improve the performance of VSG by introducing adaptive control theory to better adapt to the constantly changing power grid conditions. These studies provide a new perspective for addressing frequency fluctuations, having significant impacts on improving the stability. Wang et al. developed a method ground on polyaniline and zinc foil. A multifunctional electrochromic energy storage device using ZnCl2 salt encapsulated hydrogel as electrolyte was designed. The research results indicated that the device exhibited excellent energy storage performance, with high surface capacitance. In addition, ECESD presented excellent capacity retention and cycling performance between -25 °C to 50 °C (Wang et al. 2022a). Chen et al. used elastic gel electrolyte to create dynamic interfaces to improve the Columbia efficiency of lithium metal batteries and solve the solid electrolyte interface fracture and dead lithium formation. From the research results, the lithium metal anode maintained a high Columbia efficiency of 99.3% in 1000 cycles.

The extra long cycle life of 2000 h was achieved, which further clarified the precipitation mechanism and interface formation process of gel based lithium metal battery (Chen et al. 2022). Chen and Chang proposed an adaptive artificial bee colony optimization method for a household energy management system to optimize the residential microgrid connected to the main power grid. The research results indicated that the system could optimize the power flow allocation between photovoltaic, energy storage, and main grid based on load demand and electricity price information, minimizing power consumption costs (Chen and Chang 2023). Wang et al. added positively charged graphene chloride quantum dots to the electrolyte to construct a dual functional dynamic adaptive interface to regulate zinc deposition in aqueous zinc ion batteries and suppress side reactions. The research results indicated that this interface formed a shielding layer on the surface of Zn, promoting uniform deposition of zinc and achieving hydrophobic protection of Zn anode (Wang et al. 2023). Wang et al. proposed a defender attacker defender model to address the optimal scale and pre-positioning problem of elastic driving. The research results indicated that it determined the scale and location of energy storage systems, while evaluating potential attack scenarios (Wang et al. 2022b).

VSG technology literature review

In summary, in the field of frequency stability in new energy power systems, VSG technology has attracted much attention for simulating the inertia and damping characteristics of traditional generators. The strategy based on virtual impedance control proposed by Li M et al. can optimize the transient stability of electromechanical systems, but complex control designs pose challenges in practical applications. The reference current saturation method proposed by Saffar K G et al. improves transient stability, but the complex design limits its large-scale application. Chen T and others optimized the performance of lithium metal battery through elastic gel electrolyte, which has guiding significance for the optimization of energy storage equipment. The adaptive artificial bee colony optimization method proposed by Chen S Y et al. is effective in household energy management, but the optimization accuracy needs to be improved under variable grid load conditions. Wang Y et al.'s multifunctional electrochromic energy storage device has excellent performance, but the complexity of operation limits its application.

Therefore, the adaptive VSG technology draws on the advantages of the above research in parameter optimization and adaptive control. The study has improved the limitations of traditional VSG, especially in terms of response speed and system coordination performance. Research multiple methods to achieve higher frequency control accuracy and enhance system robustness and adaptability by adjusting parameters in real-time. These improvements aim to enhance the frequency stability of new energy power systems, while also providing solid technical support for applications in large-scale practical power grid environments.

Power system frequency based on VSG adaptive energy storage coordinated control

This study explores the frequency regulation problem in power systems. An adaptive energy storage coordination control strategy ground on VSG technology is developed. Firstly, the key role of VSG in simulating the dynamic behavior of traditional synchronous machines is analyzed. Then how the energy storage system utilizes VSG technology to achieve frequency adaptive coordinated control is elaborated in detail. Secondly, a new energy power system frequency stability response model integrating VSG control is constructed, aiming to improve the system's response ability and stability to frequency fluctuations. It is expected to provide new basis for maintaining frequency stability in the power system and demonstrate new perspectives for optimizing the operation mode of new energy grid connection.

Adaptive coordinated control strategy for energy storage based on VSG technology

The energy storage adaptive coordinated control strategy ground on VSG technology is applied in the power system. Modern computer technology are crucial for ensuring frequency stability of the power grid and improving system adaptability (Yao et al. 2023). By utilizing advanced algorithms, real-time monitoring data can be transformed into accurate power grid models. VSG technology allows control systems to deeply understand the dynamic characteristics of power systems, and thus reproduce the true dynamic behavior of the power grid (Mcglone et al. 2023). Figure 1 displays the control structure.

In Fig. 1, T_m represents mechanical torque; P, Q represent the actual output active and reactive power of VSG; E represents the internal potential of VSG. VSG technology simulates the external characteristics of synchronous machines by controlling grid connected converters, enabling new energy units to have characteristics such as inertia, damping, frequency regulation, and voltage regulation, thereby providing system frequency and voltage support, improving their adaptability and stability when connected to the power grid. The topology based on VSG includes energy storage units, converters, filters, and transmission lines, forming a model consisting of outer loop power control and inner loop current control to ensure efficient operation and reliable regulation of the system. The core feature of VSG technology is reflected in its precise coordinated control. Various components within the power system are dynamically controlled to achieve high levels of participation and responsiveness in energy storage systems (Luo et al. 2023). The stability is a key indicator to ensure the reliability and efficiency of power supply. The coordinated control efficiency of VSG technology is shown in Eq. (1).

$$\begin{cases} \eta = \sum \alpha_i \\ \alpha_i = \sum \beta_i \Phi_i \end{cases} \tag{1}$$

In Eq. (1), η represents the efficiency of coordinated control; a_i indicates the power regulation amount generated by the control strategy; β_i indicates the contribution of

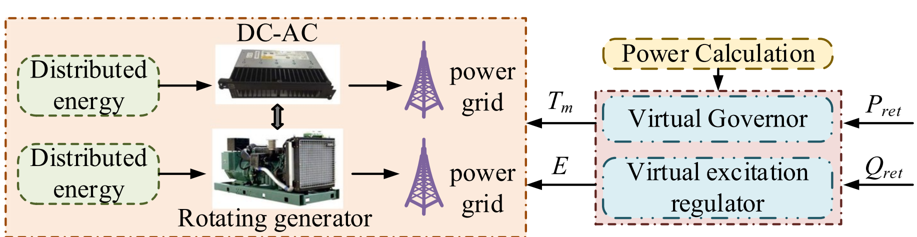


Fig. 1 VSG control structure

the i-th control strategy to frequency regulation; Φ_i stands for the importance weight of the i-th control strategy. Figure 2 displays the adaptive control strategy.

The key to the adaptive control strategy process lies in the continuous identification and adjustment of system parameters to optimize dynamic system performance. This process is based on a feedback mechanism, which dynamically adjusts the controller parameters by monitoring the difference between the system output and the expected target in real time. Firstly, monitor the frequency of the power grid in real time to determine whether energy storage power needs to be put into operation. When frequency deviation is detected to exceed the threshold, evaluate the proportional allocation coefficient of the control mode and adjust the energy storage output. If the frequency deviation reaches the maximum value, adjust the control parameters and continue to monitor frequency changes until the system frequency deviation returns to a steady-state value, ending the primary frequency adjustment. The entire process relies on feedback mechanisms to dynamically optimize system performance. The adaptive control strategy performs dimensionless processing on the original data matrix, as shown in Eq. (2).

$$Q_{nm} = \frac{C_{nm} - \overline{C}_m}{\sigma C_m} \tag{2}$$

In Eq. (2), Q_{nm} represents the real-time dimensionless value of the n-th control strategy parameter at the m-th time node; C_{nm} represents the original value of the n-th control strategy parameter at the m-th time node; $\overline{C}_m$ denotes the mean value of the control strategy parameters at the m-th time node; σC_m represents the standard value of the control strategy parameter at the m-th time node. According to the data matrix, the probability values of the contribution of each control strategy in the power system are shown in Eq. (3).

$$P_{nm} = \frac{Q_{nm}}{\sum_{k=1}^{i} Q_{nk}} \tag{3}$$

In Eq. (3), P_{nm} represents the probability value of the contribution of the n-th control strategy parameter to system frequency regulation at the m-th time node, and Q_{nm} represents the dimensionless value of the n-th control strategy parameter at the m-th time

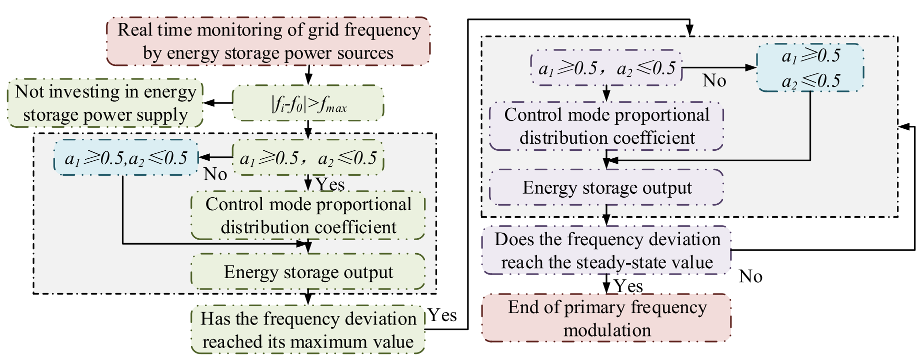


Fig. 2 Adaptive control strategy process

node; $\sum_{k=1}^{i} Q_{nm}$ denotes the sum of all dimensionless values of the n-th control strategy parameter; k indicates the index of the sum operation, ranging from 1 to i, where i represents the total number of time points. VSG technology maintains the stable operation and reflects the dynamic changes through efficient energy storage coordination control. The energy storage adaptive coordinated control framework based on VSG technology is shown in Fig. 3.

In Fig. 3, distributed energy is connected to the system through the grid interface, and real-time monitoring is carried out by the grid measurement and battery system. The inner loop current control and virtual impedance ensure current stability, and the excitation regulator regulates voltage. The Rob equation describes the dynamic response of the system, and the virtual governor simulates the inertia of the synchronous machine. Charge and discharge control optimizes battery performance, coordinates control components including model interfaces and controllers, and achieves efficient management of energy storage systems. VSG technology converts the collected power system data into a highly accurate power grid model, and fine tunes the model through coordinated control processes. Among them, the virtual regulator simulates the speed controller from the external characteristics to ensure that the output frequency has a droop characteristic. The mathematical expression is shown in Eq. (4).

$$H_m = H_{ref} + l(I_{ref} - I_g) \tag{4}$$

In Eq. (4), l is the droop proportional coefficient, which determines the degree of influence of frequency deviation on output power. The numerical frequency I_{ref} mainly refers to the rated frequency of the power system, usually a fixed value (50 Hz or 60 Hz). I_g refers to the actual frequency measured in real-time during the operation of the power system. H_m is the output power of the virtual regulator, which refers to the actual output power adjusted by the virtual regulator based on frequency deviation. H_{ref} is the reference active power value, which refers to the expected output power of the system without frequency deviation. The torque output frequency of the power difference control virtual regulator. Damping power reduces power oscillation, as shown in Eq. (5).

$$J\frac{d^2v}{dt^2} + Z\frac{dv}{dt} = H_m - H_e \tag{5}$$

In Eq. (5), Z represents the damping coefficient, which determines the attenuation rate of frequency oscillation. v represents the angular frequency of VSG output voltage, reflecting the rate of voltage variation over time; H_e indicates the actual power of the power grid; H_m denotes damping power, usually the result of input mechanical power

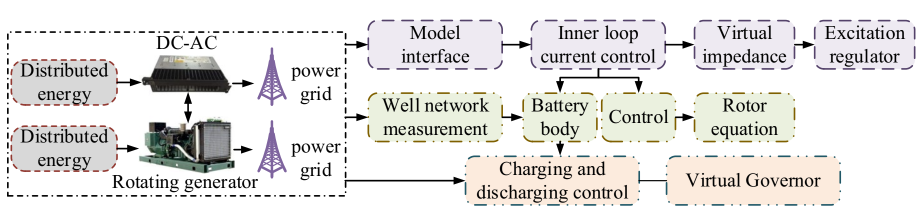


Fig. 3 An adaptive coordinated control framework for energy storage based on VSG technology

and electromagnetic conversion; J represents the virtual moment of inertia, which reflects the system's resistance to frequency changes. This technology provides a new dimension for adaptive coordinated control of power systems, helping power grid regulation achieve highly simulated control effects in a virtual environment simulating the power grid. The application of energy storage adaptive coordinated control strategy based on VSG technology in real power systems requires consideration of the dynamic characteristics and complexity of the power grid, ensuring the accuracy of real-time monitoring and control. The potential challenge lies in the real-time and accuracy of data collection and processing, as the transmission and calculation of high-frequency and large-scale data may lead to system delays and affect control effectiveness.

Construction of frequency stability response model for new energy power systems integrating VSG control

VSG technology is used to construct a highly accurate frequency response model. By integrating power grid operation data, it provides dispatchers with an intuitive control interface. The coordinated control model utilizes advanced algorithms to dynamically simulate the frequency regulation characteristics, including power flow and frequency changes, thereby enhancing control over system stability. Figure 4 presents the frequency response model.

This model utilizes SVG technology to continuously monitor power grid operation data, such as grid frequency and power flow, and provide real-time feedback on these data. Based on these real-time data, the model dynamically adjusts the controller parameters and dynamically simulates the frequency regulation characteristics, automatically adjusting the system parameters. The model adopts a centralized control perspective to provide a real-time monitoring and decision-making platform for power grid operators. The effectiveness and economy of regulation are ensured while meeting the response needs of different power grid conditions. To make the control strategy more scientific and reliable, the variation coefficient weighting method is used to evaluate the importance of each control parameter. The variation coefficient of each parameter is shown in Eq. (6).

$$CV_i = \frac{\sigma_i}{X_i} \tag{6}$$

In Eq. (6), CV_i represents the coefficient of variation of the i-th parameter, which is used to measure the relative dispersion of the parameter. The larger the coefficient of

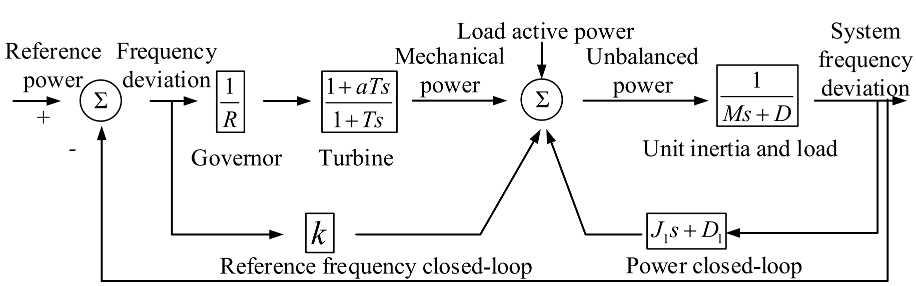


Fig. 4 Frequency response model of power system

variation, the more unstable the variation of the parameter, and the higher its importance for system control; σ_i represents the standard deviation of the i-th parameter, mainly reflecting the degree of dispersion of parameter values; X_i represents the average value of the i-th parameter, reflecting the concentration trend of the parameter. The frequency control model containing new energy is displayed in Fig. 5a.

The frequency control model introduces the characteristics of new energy generation and redefines the frequency control algorithm of traditional power systems to adapt to the high volatility and unpredictability of renewable energy. The corresponding power system benefits are statistically analyzed for their frequency response degree, as shown in Eq. (7).

$$\Delta f = SP_{svg} + CP_{res} + A\Delta P_{grid} \tag{7}$$

In Eq. (7), S represents the degree of correlation between virtual synchronous machine technology and power system frequency response, indicating the response characteristics of virtual synchronous machines in the power system; P_{svg} represents the active power output by the virtual synchronous machine, which simulates the rotational inertia characteristics of traditional synchronous generators; C represents undetermined parameters that can represent the frequency response coefficients of other renewable energy sources; P_{res} indicates the active power output of other renewable energy sources; A denotes the control effectiveness coefficient of the coordinated control strategy reflects the role of the coordinated control strategy in stabilizing system frequency; ΔP_{grid} indicates the amount of power change in the power grid, which refers to the power deviation caused by load changes. Ground on this judgment, it can be ensured that the power system frequency is both scientific and reliable. At the same time, it can also adapt to the continuous changes in new energy

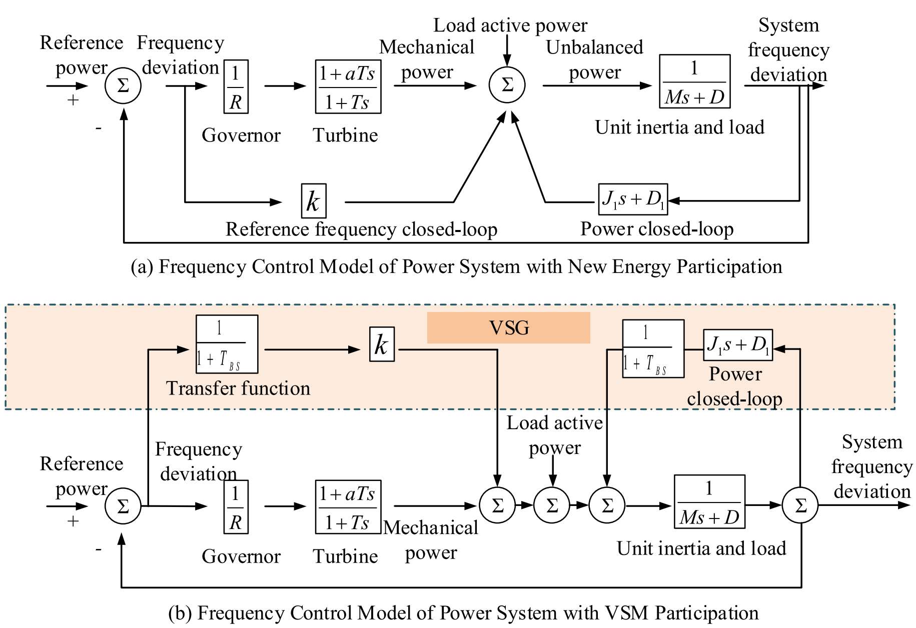


Fig. 5 Frequency control model of power system containing new energy and frequency response model ground on VSG control

and the diversity of grid demand. The frequency response model ground on VSG control is shown in Fig. 5b.

VSG technology enhances system stability in new energy power systems through precise frequency regulation and adaptive energy storage. Advanced coordinated control strategies are integrated to improve the response speed and reliability. The penetration rate of renewable energy is used to calculate the stability. The open-loop transfer function is adopted, as displayed in Eq. (8).

$$H(s) = \frac{K_d P_{re}(1 + sT_d)}{1 + s\left(T_p + T_d\right)} \tag{8}$$

In Eq. (8), $H(s)$ represents the open-loop transfer function of the system, representing the relationship between the system input and output; K_d represents the frequency modulation coefficient of the system, reflecting the magnitude of the system's frequency modulation capability and affecting the system's ability to adjust frequency changes; P_{re} represents the proportion of new energy installed capacity, reflecting the proportion of new energy generation in the total power generation, which directly affects the overall stability of the system; T_d represents the damping time constant, reflecting the response speed of the system during frequency fluctuations; T_p represents the adjustment time constant, reflecting the frequency regulation ability of the system during load changes; s represents complex variables in Laplace transform. This model reveals the coordination and control strength between different subsystems by analyzing the dynamic interaction between them, as shown in Eq. (9).

$$K = \left[\frac{c(n)p(e)q(w)}{c(n) + p(e) + q(w)/3}\right]^{\frac{1}{3}} \tag{9}$$

In Eq. (9), K represents the coordinated control force. $c(n)$ represents the power system. $p(e)$ represents system stability. $q(w)$ represents frequency control. This model can reveal the synergistic effects between different control strategies by quantifying the coordination and control efforts. The quantification of coordinated control efforts enables accurate evaluation of the contribution of various control strategies in system frequency regulation, thereby achieving more precise and efficient frequency control. This method can optimize the frequency stability response model, which helps to improve the overall performance and adaptability of new energy power systems.

The above model can provide decision support tools for the development of power grid operators, achieving real-time monitoring and dynamic adjustment functions. This tool integrates power grid operation data and frequency response models to visually display system status, and utilizes advanced algorithms to optimize control strategies. This type of interface can enhance the control ability of power system stability and help cope with the uncertainty and volatility brought by new energy generation.

Simulation analysis of power system based on VSG adaptive energy storage coordinated control

In order to verify the accuracy and reliability of the model, the study compares and analyzes it with existing classical models or measured empirical data. Evaluate the frequency response characteristics of the model under different operating conditions by comparing simulation testing with actual power system operation data. Statistical error indicators such as mean squared error (MSE) and mean absolute error (MAE) are used to quantify the accuracy of model predictions. At the same time, multi scenario simulation is applied to verify the generalization ability and adaptability of the model, ensuring stability and effectiveness under different power grid conditions.

Simulation analysis of adaptive VSG control

To effectively test and analyze the effectiveness of frequency coordination control in power systems based on VSG technology, a unified experimental environment was established for research. The simulation environment is modeled and simulated using MATLAB/Simulink R2023a version. Assuming that the power grid operates under ideal conditions and there is no external interference within the system. The software configuration adopts a real-time operating system based on Linux to optimize the efficiency of simulation operation. Model and analyze the power system using an open-source power system calculation software package. The model includes new energy generation, energy storage system, and VSG control module to simulate load fluctuations and their impact on frequency response. The initial state of charge of the energy storage system is set to 50%, taking into account the frequency changes and response characteristics under different operating conditions. The simulation time step is set to 0.01 s to ensure high-precision dynamic response analysis. The power system data collection and analysis equipment adopts high-precision digital power grid analysis instruments. The parameter settings of this model are shown in Fig. 6.

In Fig. 6, L/mH is the inductance, which affects the current change rate and transient current characteristics of the system; J is the moment of inertia. D is the damping coefficient, representing the damping characteristics of the system. k_v is the voltage regulation coefficient, which represents the degree of adjustment of voltage deviation in the control strategy, affecting the accuracy and response of voltage regulation. k_{qi} represents the reactive power regulation coefficient, which helps maintain voltage stability. k is the proportional gain, representing the gain of the proportional control part in the control system. U_{ref} is the reference voltage, representing the target voltage value during system operation. ω_{ref} is the reference angular velocity. T_p is the voltage control time constant. T_q is the time constant for reactive power control. To understand the impact of different parameters on model performance, parameter sensitivity analysis experiments were conducted, and the results are shown in Table 1.

The results show that the moment of inertia and proportional gain have a significant impact on frequency response and system stability, and higher moments of inertia and proportional gain can improve system stability and frequency response performance. The changes in damping coefficient and droop coefficient mainly affect the accuracy of oscillation amplitude and frequency response. A higher damping coefficient can effectively reduce oscillation amplitude and improve the stability of frequency response.

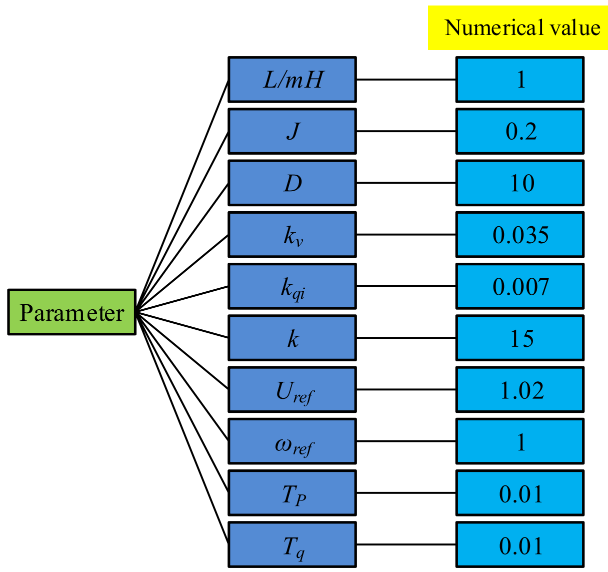


Fig.6 The parameter settings of the model

Table 1 Results of parameter sensitivity analysis

Parameter	Value range	Frequency response (Hz)	Stability (%)	Oscillation amplitude
Moment of inertia	1–10	49.5–50.3	85–95	5.6–7.3
Damping coefficient	0.5–5	49.7–50.2	80–90	6.1–6.9
Sag coefficient	1–5	49.6–50.1	83–93	6.0–7.1
Proportional gain	1–10	49.8–50.3	88–97	5.8–6.5

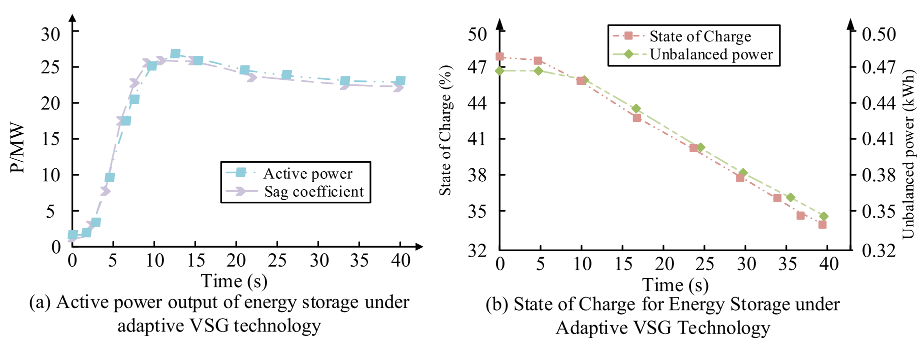


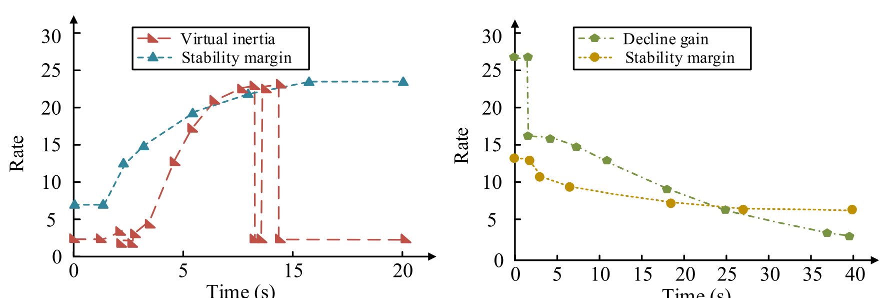
Fig. 7 Adapting to the control strategy of VSG for energy storage active power output and its state of charge

From the adaptive VSG strategy, the active power output of energy storage and its state of charge are shown in Fig. 7.

In Fig. 7 (a), the active power output capability was significantly improved, increasing from 1.32 to 24.77, reflecting the efficient intervention of the system in frequency coordination control. The droop coefficient increased from 1.26 to 23.98, indicating an improvement in response speed and sensitivity to load fluctuations, and enhancing the dynamic stability. In Fig. 7(b), the state of charge added from 47.9% to 35.8%. The unbalanced power also decreased from 0.466 kWh to 0.342 kWh. This indicates that the adaptive characteristics of VSG technology not only improve the response efficiency of energy storage systems to frequency changes, but also optimize the management of the state of charge. The virtual inertia and descent gain under adaptive VSG technology control are shown in Fig. 8.

In Fig. 8a, in the adaptive VSG technology, virtual inertia achieved a significant increase from 2.34 to 23.37 after the initial 5 s. This indicated that the energy storage system quickly adjusted its inertial response to match the immediate frequency requirements of the power system. In the following 10 to 14 s, there were significant fluctuations in virtual inertia. The fluctuation is caused by sudden changes in the grid load, and the energy storage system quickly adjusts its inertial response to adapt to new grid conditions. This fluctuation reflects the transient instability that the system needs to overcome during the adjustment process, but through adaptive control technology, the virtual inertia ultimately recovers and stabilizes at the level of 2.27, indicating the system's adaptability and stability in dealing with frequency disturbances. In Fig. 8b, the descent gain in the adaptive VSG technology showed a significant decrease after 2 s, from 26.48 to 15.83. From 2 to 40 s, the decreasing gain gradually decreased to 4.06. Adjusting the decreasing gain helped to reduce power losses caused by frequency fluctuations. The stability results of the adaptive VSG technology and VSG technology analyzed by Proy are shown in Fig. 9.

The analysis method of Proy is of great significance in evaluating the frequency stability and oscillation suppression performance of power systems. Through Proy analysis, the oscillation amplitude and frequency of the system can be accurately quantified to compare the effectiveness of different control strategies. This analysis method provides detailed frequency and time domain characteristics, providing a theoretical basis for optimizing control strategies. The Proy analysis in Fig. 9 reveals significant advantages of adaptive VSG technology over traditional VSG technology in suppressing oscillations and maintaining frequency stability. In Fig. 9a, the system under VSG technology did not show significant performance in oscillation suppression, with oscillation amplitudes of only 6.67 to 6.72, and oscillation frequencies within a narrow range, increasing from 6.23 to 6.54. This indicated that VSG technology limited effectiveness in suppressing oscillations. In Fig. 9b, the oscillation suppression effect under adaptive VSG technology was more significant. The oscillation amplitude had a greater variation, increasing from



(a) Virtual Inertia under Adaptive VSG Technology Control
(b) Descending gain under adaptive VSG technology control

Fig. 8 Virtual inertia and descending gain under adaptive VSG technology control

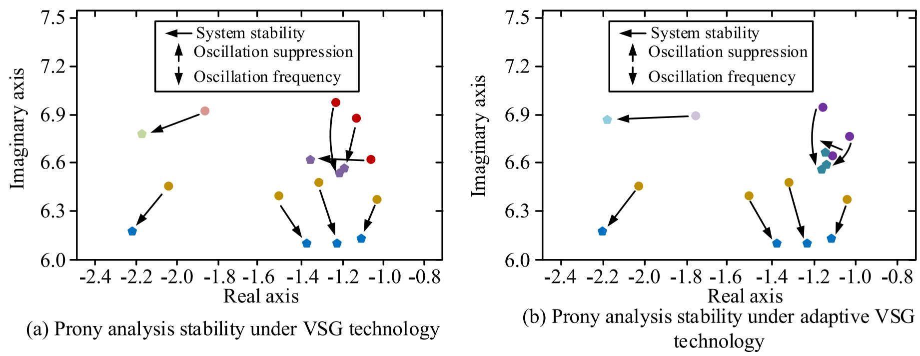


Fig. 9 Adaptive VSG technology and stability results of VSG technology analyzed by Proy

Table 2 Unit parameters with adaptive VSG and new energy power system

Unit number	Installed capacity (MW)	Equivalent inertia (J)	Regulation coefficient (%)	Droop coefficient (%)
Unit 1	300.00	3.15	5.12	4.26
Unit 2	450.00	4.64	6.07	3.35
Unit 3	500.00	5.22	4.09	5.17
Unit 4	600.00	6.18	4.55	4.86
Unit 5	800.00	8.43	3.05	6.04

6.63 to 6.84. The oscillation frequency remained within the range of 6.23 to 6.54. This indicated that adaptive VSG technology could more effectively control the oscillation amplitude while maintaining a stable oscillation frequency, thereby improving the overall stability. By dynamically adjusting the response of the energy storage system, adaptive VSG technology could more accurately match the actual demand, providing a more stable power supply and ensuring the long-term stability of the system.

Simulation verification of frequency stability response model for new energy power systems based on VSG

By analyzing the dynamic behavior of adaptive VSG technology and traditional synchronous generators, frequency stability response is thoroughly explored. According to the dynamic performance of systems under different control strategies, the performance of adaptive VSG technology is quantified, providing theoretical and technical support for the frequency regulation mechanism. The unit parameters containing adaptive VSG and new energy power system are shown in Table 2.

Table 2 shows the parameter settings of each unit in the new energy power system under adaptive VSG technology. This includes the installed capacity, equivalent inertia, adjustment coefficient, and droop coefficient index parameters of each unit, providing basic data for simulation verification. In the table, the installed capacity of the unit ranges from 300 to 800 MW, and the equivalent inertia increases with the increase of installed capacity, with a maximum of 8.43 (unit 5) and a minimum of 3.15 (unit 1). The difference in values between the adjustment coefficient and the droop coefficient is significant, with the highest adjustment coefficient being 6.07% (unit 2) and the lowest being 3.05% (unit 5); The sag coefficient varies between 3.35% (unit 2) and 6.04% (unit 5). The parameter configuration of each unit helps adaptive VSG technology achieve better frequency control effects under different operating conditions. The frequency response results are displayed in Fig. 9.

Introducing energy storage units in wind and photovoltaic systems can smooth output power and enhance system schedulability. These schedulable new energy resources can provide frequency and voltage support under VSG control strategy, thereby enhancing the stability and reliability of the power system. The key difference between adaptive VSG technology and traditional VSG technology is that the former can adjust parameters in real-time based on system status, thereby achieving more accurate frequency control. According to Fig. 10, in the adaptive VSG technology, the peak frequency of wind power was 50.27 Hz, and the lowest value was 49.51 Hz. The peak frequency of photovoltaic power generation was 50.18 Hz, and the lowest value was 49.62 Hz. This indicated that adaptive VSG technology could remain frequency within a narrow range and improve the stability. In the VSG technology, the peak frequency of wind power was only 50.16 Hz, with a minimum value of 49.68 Hz. The frequency of photovoltaic power generation showed a small variation, with a peak of 50.11 Hz and a minimum of 49.73 Hz. The VSG technology provides frequency control. However, compared with adaptive VSG technology, its ability to suppress frequency fluctuations was weaker. In addition, for energy storage systems, when their State of Charge (SoC) reaches its limit, energy recovery control is required to prevent overcharging or discharging of energy storage equipment, thereby ensuring the long-term stable operation of the system. Therefore, the implementation of VSG needs to consider the actual operational limitations of wind turbines and energy storage equipment. The frequency response results of the new energy power system without participating in primary frequency regulation and providing system inertia are shown in Fig. 11.

In Fig. 11a, the frequency fluctuation was severe under VSG technology. When not participating in primary frequency regulation and not providing system inertia, the system stability index was as low as 29.47, indicating insufficient adaptability to load changes. In Fig. 11b, in the adaptive VSG technology, the system compatibility and stability indicators were significantly improved, increasing from 44.65 and 1.16 to 53.18 and 85.22, respectively. The performance benchmark and system maintainability also increased from 60.95 and 10.08 to 74.29 and 95.57, respectively,

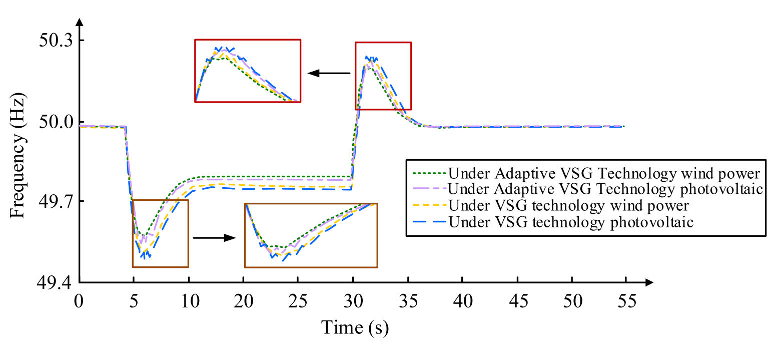
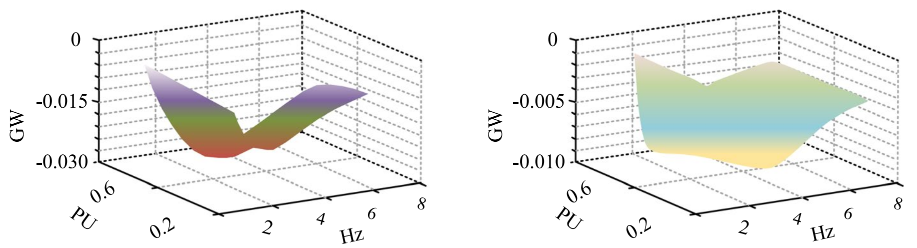


Fig. 10 Frequency response results of new energy power system based on VSG



(a) The influence of parameter a on the frequency response of power systems

(b) The influence of parameter a on the frequency response of power systems

Fig. 11 Frequency response of new energy power systems without participating in primary frequency regulation and providing system inertia

Table 3 System Frequency Response and Stability Indicators under Different Control Strategies

Control strategy	Peak frequency (Hz)	Minimum frequency value (Hz)	Stability index (%/kW)	System completion efficiency (%)
Adaptive VSG	50.27	49.51	85.22	75.39
Traditional VSG	50.16	49.68	44.65	53.18
Sag control	50.15	49.64	50.87	60.22
Not using VSG	50.11	49.73	29.47	4.98

demonstrating the contribution of VSG technology to the robust operation of power systems. Adaptive VSG technology significantly improved system completion efficiency without providing system inertia support, increasing from 4.98 to 75.39. The stability index results reflect the adaptability of the technology to load changes. The higher the index, the stronger the adaptability. The technology has obvious advantages in enhancing system robustness and maintaining frequency stability. Therefore, adaptive VSG technology had a significant positive impact on improving the adaptive energy storage coordination control and frequency stability of new energy power systems. To further enhance the comprehensiveness of the comparison, the experimental results of the currently popular droop control strategy were added and compared with the results of adaptive VSG, traditional VSG, and those without VSG. The results are shown in Table 3.

In the table, adaptive VSG technology exhibits the optimal frequency control capability, with the minimum range of peak and minimum frequency values, ensuring the highest system stability index and completion efficiency. Traditional VSG and droop control strategies are slightly inferior in frequency fluctuation control, especially in stability indicators and system completion efficiency. Adaptive VSG has improved by 40.57% and 22.21%, respectively. In contrast, the droop control strategy performs suboptimal, outperforming traditional VSG and non VSG, but still lags behind adaptive VSG in terms of frequency control accuracy and system stability. Therefore, adaptive VSG technology is significantly superior to other control strategies in terms of dynamic response and frequency and voltage regulation, providing a more robust solution for frequency regulation in new energy power systems.

Discussion

The study explores the application efficiency of adaptive VSG technology in frequency control of power systems, and verifies its significant improvement in frequency stability and dynamic response through experiments. The results show that adaptive VSG technology performs the best in frequency response, with the smallest frequency fluctuation range. The system stability index and completion efficiency are significantly higher than traditional VSG technology and droop control strategy. The main reason is that adaptive VSG technology can adjust parameters in real-time based on the actual state of the power system, achieving more accurate frequency control. Compared with the robust control of hybrid energy storage systems based on Type 2 fuzzy observers proposed by Ghavier H. F et al., this study highlights the significant improvement of frequency control accuracy by adaptive VSG technology. Adaptive VSG technology can adjust parameters in real-time, making it more sensitive and efficient than traditional fuzzy control (Ghavidel and Mousavi-G 2022). The adaptive multi-mode switching control strategy proposed by Liu Z et al. aims to improve the stability of virtual synchronous generators (Liu et al. 2023). Compared to this, adaptive VSG technology significantly improves system stability and completion efficiency without participating in primary frequency modulation. Li M et al. study on dynamic power coupling of grid to grid converters shows that adaptive VSG technology performs better in handling frequency fluctuations and stabilizing system frequencies (Li et al. 2022b).

This study validated the advantages of adaptive VSG technology through experimental data, demonstrating its excellent performance in dynamic response and frequency regulation, providing a more robust solution for frequency regulation in new energy power systems. This is of great significance for the smooth operation of the power system and the maintenance of grid frequency, providing effective technical support for grid operators and decision-makers.

Future research should further optimize the adaptive VSG control strategy, consider more complex power grid operation scenarios, and verify its adaptability and reliability to different types of power grids through larger scale experiments.

Conclusion

With the rapid progress of new energy power systems, system frequency stability has faced unprecedented challenges. In modern power systems with massive renewable energy connected to the grid, frequency stability is an important factor in maintaining the reliable operation. Based on this background, an adaptive VSG energy storage coordination control strategy was developed to enhance the adaptive regulation ability. From the research results, in the adaptive VSG technology, the frequency stability of wind power was significantly improved, with a peak frequency stable at 50.27 Hz and a minimum value of 49.51 Hz. The peak frequency of photovoltaic power generation was 50.18 Hz, and the minimum value was 49.62 Hz. In the VSG technology, the frequency stability of wind and photovoltaic power generation systems was significantly poor, with the peak and minimum values of wind frequency being 50.16 Hz and 49.68 Hz, respectively, and the peak and minimum values of photovoltaic frequency being 50.11 Hz and 49.73 Hz, respectively. In addition, the adaptive VSG technology improved the system stability index from 29.47 to 85.22 without providing system inertia support. The performance benchmark and system maintainability indicators were also improved from 60.95 and 10.08 to 74.29 and 95.57, respectively, indicating the significant effect of this technology in improving system stability.

The proposed adaptive VSG energy storage coordination control strategy significantly improves the frequency stability of high proportion renewable energy grid connection in modern power systems. The novelty of this strategy lies in its adaptive adjustment ability, which can adjust control parameters in real-time to more efficiently respond to frequency fluctuations and stabilize the power grid, and has important energy informatics significance. However, there are also some limitations to the research, such as challenges in cost control, technology integration, and large-scale applications that have not been fully resolved. These limitations partially affect the widespread applicability of the results, indicating that further validation and optimization are still needed in practical applications.

Future research can be carried out from the following aspects: further optimizing adaptive VSG control strategies, exploring methods to reduce the cost of adaptive VSG technology, and optimizing solutions for technology integration; Study its applicability and reliability in larger scale complex power systems; Strengthen the integration with other control strategies to further enhance the system's adaptability and robustness.

Author contributions
Min Cheng, Wenlin Yan, Dan Zhang, Xufei Liu, Lei He, Mingyu Xu, Qiang Yao participated in the writing, review and editing of the article.

Funding
There is no funding.

Availability of data and materials
The data are within the manuscript.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that this paper is no conflict of interest.

Received: 7 May 2024 Accepted: 23 June 2024
Published online: 04 July 2024

References
Chen SY, Chang CH (2023) Optimal power flows control for home energy management with renewable energy and energy storage systems. IEEE Trans Energy Convers 38(1):218–229
Chen T, Wan J, Liu Y (2022) A tough, elastic ion gel with adaptive interface for high performance and safe lithium metal anodes. Chem Eng J 433(2):2–8
Chen J , Zeng Q , Li G , Xin Y, Li L, Wang P. Deviation-Free Frequency Control of MMC-MTDC Converter Based on Improved VSG//2019 4th IEEE Workshop on the Electronic Grid (eGRID).IEEE, 2019, 1–5
Ghavidel HF, Mousavi-G SM (2022) Observer-based type-2 fuzzy approach for robust control and energy management strategy of hybrid energy storage systems. Int J Hydrogen Energy 47(33):14983–15000
Goud V, Rahul MR, Phanikumar G (2022) Prediction of growth velocity of undercooled multicomponent metallic alloys using a machine learning approach. Scripta Mater 207(1):2–6
Li M, Shu S, Wang Y, Yu P, Liu Y, Zhang Z et al (2022a) Analysis and improvement of large-disturbance stability for grid-connected VSG based on output impedance optimization. IEEE Trans Power Electron 37(8):9807–9826

Li M, Wang Y, Hu W, Shu S, Yu P, Zhang Z et al (2022b) Unified modeling and analysis of dynamic power coupling for grid-forming converters. IEEE Trans Power Electron 37(2):2321–2337
Liu Z, Qin L, Zhou Y, Lei X, Huangfu C, Yang S et al (2023) An adaptive multi-mode switching control strategy to improve the stability of virtual synchronous generator with wide power grid strengths variation. IET Gener Transm Distrib 17(2):307–323
Luo N, Yu H, You Z, Li Y, Zhou T, Han N et al (2023) Fuzzy logic and neural network-based risk assessment model for import and export enterprises: a review. J Data Sci Intell Syst 1(1):2–11
Mcglone ER, Siebert M, Dore M, Hope DCD, Davies I, Owen B et al (2023) Sleeve gastrectomy causes weight-loss independent improvements in hepatic steatosis. Liver Int 43(9):1890–1900
Perez F. Control of ac/dc microgrids with renewables in the context of smart grids: Including ancillary services and electric mobility. Diss. Université Paris-Saclay; Universidade federal de Itajuba. Brésil, 2020.
Saffar KG, Driss S, Ajaei FB (2023) Impacts of current limiting on the transient stability of the virtual synchronous generator. IEEE Trans Power Electron 38(3):1509–1521
Srivastava A, Stevenson M, Lee J, Hall C, Palaia T, Zhao CL et al (2022) Reversal of NAFLD after VSG is independent of weight-loss but RYGB offers more efficacy when maintained on a high-fat diet. Obes Surg 32(6):2010–2022
Sun C, Geza J, Francois B (2019) Identification of low-frequency oscillation mode and improved damping design for virtual synchronous machines in microgrid. IET Gener Transm Distrib 13(14):2993–3001
Sun Q, Quanrui H, Li D. An Operating Limit Control Strategy of VSG with Constraints of Internal Variables. 2023 International Conference on Power System Technology (PowerCon). IEEE, 2023, 1–6.
Wang Y, Zhong X, Liu X, Lu Z, Su Y, Wang M et al (2022a) A fast self-charging and temperature adaptive electrochromic energy storage device. J Mater Chem A 10(8):3944–3952
Wang Y, Rousis AO, Strbac G (2022b) Resilience-driven optimal sizing and pre-positioning of mobile energy storage systems in decentralized networked microgrids. Appl Energy 305(1):2–13
Wang HR, Zhou AB, Hu X, Hu ZQ, Zhang FL, Huang YX et al (2023) Bifunctional dynamic adaptive interphase reconfiguration for zinc deposition modulation and side reaction suppression in aqueous zinc ion batteries. ACS Nano 17(12):11946–11956
Xiao T, Liu Z, Lu L, Han H, Huang X, Song X (2023) LSTM-BP neural network analysis on solid-liquid phase change in a multi-channel thermal storage tank. Eng Anal Boundary Elem 146(1):226–240
Xuan ZR, Alexandros M, Els P (2022) The spatially resolved PAH characteristics in the Whirlpool Galaxy (M51a). Mon Not R Astron Soc 511(4):5142–5157
Yao G, Luo Z, Lu Z, Wang M, Shang J, Guerrerob JM (2023) Principle and control strategy of a novel wave-to-wire system embedded ocean energy storage optimization. Ocean Eng 271(1):2–14

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