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A smooth grid connection strategy for compressed air energy storage based on adaptive PI control

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In the context of the application of compressed air energy storage system participating in power grid regulation, a large capacity of compressed air energy storage accessed to or off from the power grid will bring instability to the system, and there will be voltage and current impact during off-grid operation, which will pose a threat to system security. Therefore, this paper puts forward the control strategy of compressed air energy storage for both grid-connected and off-grid, and proposes a smooth grid-connected strategy of compressed air energy storage based on adaptive PI control, which can better improve the problem of excessive impulse current during the connection of compressed air energy storage. Finally, a simulation model is built in MATLAB/Simulink to verify the effectiveness and superiority of the proposed control strategy.

KEYWORDS

compressed air energy storage¹, grid-connected and off-grid control strategies², smooth grid connection³, PI control⁴, impulse current⁵

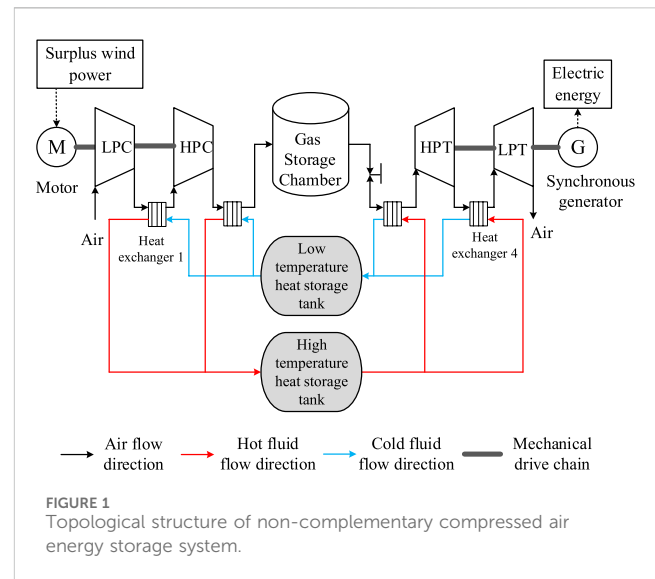
1 Introduction

Compressed air energy storage, due to its large energy storage capacity and high conversion efficiency, is suitable for commercial application in large-scale energy storage power plants. It is one of the key technologies to solve the problems of volatile renewable energy consumption, power grid peak shaving, carbon compliance, and carbon neutrality (Mei S et al., 2017; Liu et al., 2023; Chen et al., 2016; Attarha et al., 2018). Compressed air energy storage has the characteristics of storing and converting three forms of energy: cold, heat, and electricity (R. Khatami et al., 2020). Through multi-energy cogeneration, high energy comprehensive utilization efficiency (70%–80%) can be achieved to make up for the lack of low power conversion efficiency of compressed air energy storage, thereby effectively improving the application economy of compressed air energy storage (A. Azizivahed et al., 2020).

In terms of the application of compressed air energy storage in power grid regulation, compressed air energy storage is used to smooth the fluctuations of wind power and improve the quality of wind power, so as to increase the utilization level of wind power and its penetration rate in the power grid (Cleary et al., 2015; Cheng et al., 2019; Zhu et al., 2023). Reference (Wen X et al., 2021) studies the participation of compressed air energy storage systems in primary frequency regulation and proposed a method for the compressed air

energy storage system to participate bidirectionally in response to the primary frequency regulation of the power grid in the two stages of energy storage and energy release. Reference (Li G et al., 2021) proposes a phase modulation operation mode based on compressed air energy storage power plants, which achieves the function of supporting reactive power and voltage of the power grid and verifies the rationality of phase modulation operation of salt cavern compressed air energy storage power plants. Reference (Aldaadi et al., 2021) proposes a grid-connected power optimization strategy based on segmented real-time wind power and electricity price data averaging to ensure continuous and stable output of power to the grid. Reference (Xu W et al., 2022) proposes a new configuration that uses compressed air energy storage to assist wind turbines to increase the total power generation and schedulability of wind power generation, and verifies its effectiveness in realizing a schedulable wind energy conversion system through case studies. Reference (Meng et al., 2023) proposes a compressed air energy storage multi-energy co-supply system coupled with thermal power, evaluates its thermal performance and technical economy, and provides a new development idea for the large-scale commercial application of compressed air energy storage. Reference (Cheng J et al., 2018) proposed an advanced adiabatic compressed air energy storage multi-energy flow optimization scheduling model based on energy hub matrix modeling, proving that advanced adiabatic compressed air energy storage can realize daily hot spot joint supply and improve regional energy utilization efficiency.

Compressed air energy storage can operate independently with load and can also be connected to the power grid to participate in grid regulation. However, during the grid connection process, if the conditions of equal phase frequency to the grid voltage are not met, large impulse currents and voltages will usually be generated, threatening the safe and stable operation of equipment. Therefore, a smooth grid connection strategy is needed to ensure the smooth and safe connection of compressed air energy storage to the power grid. For smooth switching, reference (Xiong et al., 2016) adopts the methods of V/f control and PQ control switching, and introduces current compensation to reduce the transient impact before and after switching the control strategy. References (Wang et al., 2016; Zheng F et al., 2019) use a virtual synchronous generator to switch to PQ control, and controls the current loop instructions to ensure that the inner loop parameters are consistent when the control mode is switched to achieve smooth switching. Reference proposes a smooth grid connection strategy for optical storage virtual synchronous machines based on adaptive model predictive control. On the basis of the model predictive control strategy, frequency variation is introduced to adaptively adjust the weighting coefficient, which effectively improves the voltage and current surge problem during the switching process. Reference (Yuan et al., 2017) proposes a smooth switching control strategy for microgrid operation mode based on linear active disturbance rejection control technology, achieving the effect of quickly eliminating disturbances and smoothing the switching process. Reference (Xiong et al., 2016) proposes a new phase-locked loop suitable for microgrid systems based on the smooth switching control method of microgrid under master-slave control conditions to ensure smooth switching of microgrid operation modes and enhance system stability. At present, research on smooth switching focuses on microgrids, and there is little



research on the issue of compressed air energy storage and smooth grid connection to reduce impulse voltage and current.

In order to solve the impact problem caused by the grid connection of compressed air energy storage, this paper proposes a smooth grid connection control strategy based on adaptive PI control after proposing control strategies for the compressed air energy storage system in both grid-connection and off-grid modes. Finally, a simulation model of compressed air energy storage was built on the MATLAB/SIMULINK simulation platform, and the proposed control strategy was experimentally verified.

2 Structure and modeling of compressed air energy storage system

Compressed air energy storage refers to the use of low valley electricity, wind power curtailment and photovoltaic power, etc., to compress the air through a compressor, and store high-pressure air in a sealed storage chamber. During peak electricity consumption period, the air is released to drive a turbine to generate electricity.

2.1 Structure of compressed air energy storage system

This paper builds an advanced adiabatic compressed air energy storage system, and the topology diagram of the system is shown in Figure 1. The system consists of an electric motor, a compressor unit, a gas storage tank, a heat storage system, an expansion unit, and a generator. During the low period of electricity consumption, surplus wind power is used to drive the compressor to compress the air through two stages of compression, generating high-temperature and high-pressure air that enters the heat exchanger on the compression side for heat exchange with the heat transfer oil. The heat transfer oil absorbs heat and heats up before entering the high-temperature heat transfer oil tank. The compressed air releases heat and cools down to the environmental temperature before entering the salt cavern gas storage tank for storage; During

electricity peak period, high-pressure air is released from the gas storage, heated by high-temperature thermal oil in the oil-gas heat exchanger on the power generation side, and then enters the secondary air turbine with an intermediate reheater to expand and perform work to complete the power generation process (Shengwei et al., 2022).

2.2 Modeling of compressed air energy storage system

This paper establishes a mathematical model for the operation of advanced adiabatic compressed air energy storage system under reasonable simplified conditions based on the thermodynamic, heat transfer, fluid mechanics, and electrical mechanisms of the main devices in the system (I. Calero et al., 2020; Mirzapour-Kamanaj et al., 2022). The mathematical model of each device is shown in Eqs 1–21.

1) Mathematical model of compressor

The continuous equation is as follows:

$$m_{i,c} = m_{e,c} \quad (1)$$

The compressor outlet air temperature equation is as follows:

$$T_{e,c} = T_{i,c} \left(1 + \frac{\pi^{\frac{k-1}{k}} - 1}{n_s} \right) \quad (2)$$

The compressor power equation is as follows:

$$N_c = m(h_{e,c} - h_{i,c})n_s \quad (3)$$

The compressor outlet pressure equation is as follows:

$$P_{e,c} = \pi P_{i,c} \quad (4)$$

The number of compression stages is expressed as follows:

$$S = \ln \pi_z / \ln \pi \quad (5)$$

where $m_{i,c}$ and $m_{e,c}$ are the air mass flow rates at the inlet and outlet of the compressor, kg/min; $T_{i,c}$ and $T_{e,c}$ are the inlet and outlet air temperatures of the compressor, K; k is the specific heat ratio of air; n_s is the adiabatic efficiency of the compressor; m is the air mass flow rate inside the compressor, kg/min; N_c is the input power of the compressor, kW; $h_{i,c}$ and $h_{e,c}$ are the specific enthalpies of the inlet and outlet air of the compressor, kJ/kg; $P_{i,c}$ and $P_{e,c}$ are the inlet and outlet air pressures of the compressor, MPa; π is the single stage pressure ratio of the compressor, π_z is the total pressure ratio of the compressor; S is the number of compressor stages.

2) Mathematical model of heat exchanger

The heat exchanger model in the energy storage stage is basically the same as the heat exchanger model in the energy release stage, with the difference being that the air in the heat exchanger during the energy storage stage releases heat, while the water absorbs heat;

During the energy release stage, the air in the heat exchanger absorbs heat, while the water releases heat.

The air energy balance equation is as follows:

$$M_a C_{pa} \frac{dT_{ae,c}}{dt} = m C_{pa} (T_{ai,c} - T_{ae,c}) - Q_1 \quad (6)$$

The metal heat storage equation is as follows:

$$M_t C_t \frac{dT_t}{dt} = Q_1 - Q_2 \quad (7)$$

The cooling water energy balance equation is as follows:

$$M_w C_{pw} \frac{dT_{we,c}}{dt} = G_{w,c} C_{pw} (T_{wi,c} - T_{we,c}) + Q_2 \quad (8)$$

The heat transfer equation is as follows:

$$Q_1 = \alpha_1 A \left(\frac{T_{ai,c} + T_{ae,c}}{2} - T_t \right) \quad (9)$$

$$Q_2 = \alpha_2 A \left(T_t - \frac{T_{wi,c} + T_{we,c}}{2} \right)$$

The energy efficiency equation is as follows:

$$\varepsilon = \frac{T_{ae,c} - T_{ai,c}}{T_{wi,c} - T_{ai,c}} \quad (10)$$

The pressure drop equation is as follows:

$$\Delta P = \left(\frac{0.0083\varepsilon}{1 - \varepsilon} \right) P_{ai,c} \quad (11)$$

$$P_{ae,c} = P_{ai,c} - \Delta P$$

Where, M_a , M_t , M_w are the air mass in the heat exchanger, the metal pipe mass of the heat exchanger, and the water mass inside the heat exchanger, kg; C_{pa} , C_t , and C_{pw} are the specific heat capacity of the air at constant pressure, metal tube specific heat capacity, and water specific heat capacity in the heat exchanger, kJ/(kg*K); m is the air mass flow rate inside the heat exchanger, kg/min; G_w is the mass flow rate of water inside the heat exchanger; $T_{ai,c}$ and $T_{ae,c}$ are the inlet and outlet air temperatures of the heat exchanger, K; T_t is the temperature of the metal tube of the heat exchanger, K; $T_{wi,c}$ and $T_{we,c}$ are the temperatures of the inlet and outlet water in the heat exchanger, K; Q_1 is the energy released by air, kJ; Q_2 is the energy absorbed by water, kJ; α_1 and α_2 are the heat transfer coefficient of air and water, kJ/(m²*min*K); A is the heat exchange area, m²; ε is the energy efficiency of the heat exchanger; $P_{ai,c}$ and $P_{ae,c}$ are the air pressure at the inlet and outlet of the heat exchanger, MPa.

3) Mathematical model of gas storage tank

In this paper, the process of storing high-pressure gas in advanced adiabatic compressed air storage system is regarded as a constant volume process, energy is not released during storage, and air liquefaction is not considered. The pressure and temperature changes in the storage tank are mainly studied, and air is regarded as an ideal state.

The energy balance equation of gas storage tank in energy storage stage is as follows:

$$\frac{d(M_v v)}{dt} = C_{pa} m_c T_{vi} - \alpha_3 A_v (T_v - T_h) \quad (12)$$

The energy balance equation of gas storage tank in energy release stage is as follows:

$$\frac{d(M_v v)}{dt} = -C_{pa} m_s T_{ve} - \alpha_3 A_v (T_v - T_h) \quad (13)$$

The change trend of air pressure and temperature in storage tank during energy storage stage is expressed as follows:

$$\frac{dp_v}{dt} = \frac{C_{pa} m_c T_{vi} - \alpha_3 A_v (T_v - T_h)}{C_{va} V} R_g \quad (14)$$

$$\frac{dT_v}{dt} = \frac{C_{pa} m_c T_{vi} - \alpha_3 A_v (T_v - T_h) - C_{va} m_c T_v}{C_{va} V P_v} R_g T_v \quad (15)$$

The change trend of air pressure and temperature in the tank during energy release is expressed as follows:

$$\frac{dp_v}{dt} = \frac{-C_{pa} m_s T_{ve} - \alpha_3 A_v (T_v - T_h)}{C_{va} V} R_g \quad (16)$$

$$\frac{dT_v}{dt} = \frac{-C_{pa} m_s T_{ve} - \alpha_3 A_v (T_v - T_h) + C_{va} m_s T_v}{C_{va} V P_v} R_g T_v \quad (17)$$

Where, P_v is the air pressure of the air storage tank, kPa; V is the volume of the air storage tank, m³; m_c and m_s are the air mass flow at the inlet and outlet of the air storage tank, kg/min; α_3 is the heat exchange coefficient of the air storage tank, W/(m²*K); M_v is the gas mass in the air storage tank, kg; v is the internal energy per unit mass of the gas in the air storage tank, kJ/kg; A_v is the heat exchange area of the air storage tank, m²; T_h is the ambient temperature, K; T_{vi} and T_{ve} are the air temperature at the inlet and outlet of the air storage tank, K; C_{va} is the specific heat capacity of air at constant volume, kJ/(kg*K); R_g is the gas constant, kJ/(kg*K). T_v is the air temperature in the tank, K.

4) Turbine mathematical model

The operation mechanism of turbine can be understood as the inverse process of compressor. The mathematical model of turbine is established by compressor modeling method.

$$m_{i,s} = m_{e,s} \quad (18)$$

The turbine outlet air temperature equation is as follows:

$$T_{e,s} = T_{i,s} \left(1 - \left(1 - \frac{1}{\pi^{\frac{k-1}{k}}} \right) n_s \right) \quad (19)$$

The turbine power equation is as follows:

$$N_s = m_s (h_{i,s} - h_{e,s}) n_s \quad (20)$$

The turbine outlet pressure equation is as follows:

$$P_{e,s} = \frac{P_{i,s}}{\pi} \quad (21)$$

Where, $m_{i,s}$ and $m_{e,s}$ are the air mass flow at the inlet and outlet of turbine, kg/min; $T_{i,s}$, $T_{e,s}$ are the air temperature at the inlet and outlet of turbine, K; k is the specific heat ratio of air; n_s is the adiabatic efficiency of turbine; m is the mass flow in turbine, kg/min; N_s is the output power of turbine, kW; $h_{i,s}$ and $h_{e,s}$ are the air

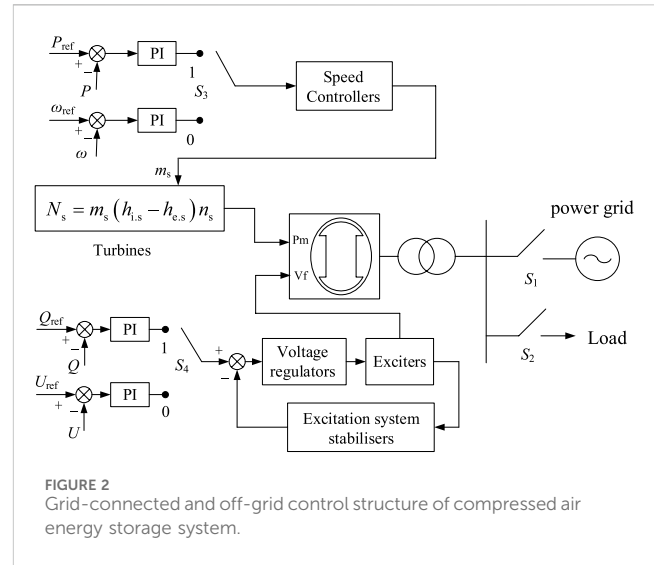


FIGURE 2 Grid-connected and off-grid control structure of compressed air energy storage system. specific enthalpy at the inlet and outlet of turbine, kJ/kg; $P_{i,s}$ and $P_{e,s}$ are the air pressure at the inlet and outlet of turbine, MPa.

3 Compressed air energy storage smooth grid-connection strategy based on PI control

3.1 Grid-connected control structure and off-grid control structure of compressed air energy storage system

PQ control strategy is adopted when the compressed air energy storage system is connected to the grid, and V/f control strategy is adopted when the compressed air energy storage system is off the grid.

The coordinated control of grid-connected and off-grid modes enhances power supply reliability. Based on the above two control strategies, a control structure for compressed air energy storage systems operating in both grid-connected and off-grid modes is constructed, as shown in Figure 2.

3.2 Control strategy of compressed air energy storage system connected to grid

PQ control strategy is adopted for grid-connected mode operation of compressed air storage. The fluctuation of load, frequency and voltage carried by compressed air storage are borne by the large power grid. Compressed air storage does not need to consider the regulation of voltage and frequency, but is directly controlled and regulated according to the voltage and frequency of the power grid. Compressed air storage outputs active and reactive power according to a given reference value. In this way, compressed air energy storage only needs to emit or absorb power, which can avoid interference to the power system caused by compressed air energy storage participating in voltage regulation of the power grid.

The active power P output by that synchronous generator is compared with a reference value P_{ref} to make a difference, then PI regulation is carry out, after PI regulation, the active power P enters a speed governor link to obtain air mas flow m_s , m_s is then input into a turbine for compressed air energy storage, wherein the turbine is equivalent to a prime mover in a conventional generator set, the air mass flow m_s is equivalent to a steam valve opening of the turbine, and mechanical power P_m generated by expansion air of the turbine drives the synchronous generator to complete power generation. The process of generating power by compressed air energy storage system can be expressed by Equation 20.

The output reactive power Q and the reference value Q_{ref} of the synchronous generator are compared. After PI regulation, the excitation voltage of the exciter is obtained to control the output voltage of the exciter, that is, the excitation voltage V_f of the generator, and then input into the synchronous generator. In order to stabilize the operation of the excitation system and improve its dynamic quality, the negative feedback link of the excitation system is introduced, that is, the excitation system stabilizer, which is generally a soft feedback link, also known as speed feedback.

3.3 Off-grid control strategy for compressed air energy storage system

V/f control strategy is adopted for compressed air storage off-grid mode operation. When the power grid fails or scheduled maintenance occurs, the compressed air storage system needs to disconnect the common connection point with the power grid to realize off-grid operation, providing voltage and frequency support to ensure that the amplitude of frequency and output voltage is always controlled within the allowable range, regardless of how the output power changes, so as to ensure the normal and stable operation of the compressed air storage system off-grid.

When the compressed air energy storage system operates off-grid with V/f control strategy, the amplitude of output voltage V is obtained by measuring module, and then the frequency f is obtained by phase-locked loop. The amplitude of output voltage V is compared with reference value V_{ref} , and then the excitation voltage V_f is obtained by exciter and input to synchronous generator. The frequency f is compared with the reference value f_{ref} , and after PI regulation, the air mass flow m_s is obtained through the speed governor and input into the turbine for compressed air energy storage. The mechanical power generated by the turbine expansion air is used as the mechanical power P_m of the prime mover to drive the synchronous generator to complete power generation.

3.4 Compressed air energy storage smooth grid-connection strategy based on adaptive PI control

When the compressed air energy storage system is connected to the grid, the compressed air energy storage system voltage needs to be the same as the grid voltage in amplitude, phase and frequency. If the conditions cannot be met, there will be a large voltage difference

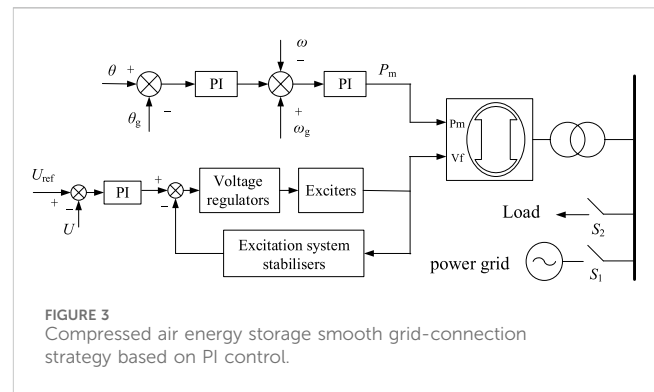


FIGURE 3
Compressed air energy storage smooth grid-connection strategy based on PI control.

when the grid switch is closed, which will lead to excessive grid impulse current and pose a threat to the system safety. Therefore, the output voltage of the compressed air energy storage system needs to match the grid voltage in amplitude, frequency and phase before grid-connection. In the voltage control of compressed air energy storage, the reference voltage has been set as the grid side voltage, so this paper mainly studies the control strategy of frequency and phase Angle. The control block diagram of compressed air energy storage smooth grid connection strategy based on PI control is shown in Figure 3.

In Figure 3, θ is the compressed air energy storage side voltage phase angle, θ_g is the grid side voltage phase angle, ω is the compressed air energy storage side angular frequency, and ω_g is the grid side angular frequency. The phase difference between the compressed air storage output phase and the power grid is first controlled by PI, and its deviation value is introduced into the angular frequency deviation, and then P_m is obtained through PI control. This process can pre-synchronize the phase difference and frequency difference between the compressed air energy storage and the power grid, so that the phase difference and frequency difference between the compressed air energy storage and the power grid can be minimized when connected to the grid, so as to reduce the impulse current of the grid-connection.

In order to control the phase and frequency synchronization process of compressed air energy storage more accurately, the k_p and k_i parameters of PI regulator are adjusted adaptatively on the basis of PI control, so as to achieve the purpose of rapid response of the system and precise adjustment of phase and frequency pre-synchronization. k_p and k_i are proportional coefficients and integral coefficients respectively. The larger k_p is, the faster the system responds, but too large k_p will cause the instability of the system. k_i improves the stability of the system, but the larger k_i increases the overshoot and even the oscillation of the system. Therefore, in the pre-synchronization process, when the phase difference between the energy storage side and the network side is large, k_p and k_i are increased to improve the system response speed and reduce the pre-synchronization time. When the phase difference between the energy storage side and the network side is small, and the phase difference is close to the grid-connected requirements, in order to reduce the phase difference too fast and cause the system frequency instability, reduce k_p and k_i at this time. The adaptive PI control designed in this paper is shown in Eqs 22, 23:

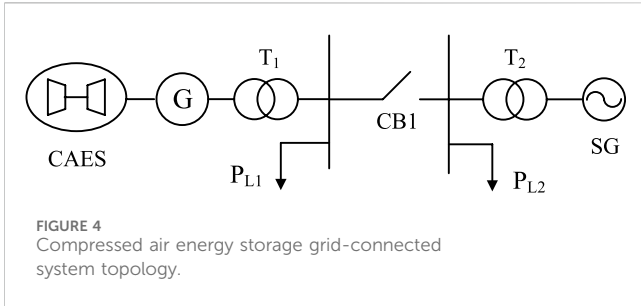


FIGURE 4 Compressed air energy storage grid-connected system topology.

$$k_p = \begin{cases} k_{p0} + \Delta k_p & \Delta \theta > 15^\circ \\ k_{p0} - \Delta k_p & \Delta \theta < 15^\circ \end{cases} \quad (22)$$

$$k_i = \begin{cases} k_{i0} + \Delta k_i & \Delta \theta > 15^\circ \\ k_{i0} - \Delta k_i & \Delta \theta < 15^\circ \end{cases} \quad (23)$$

In the formula, k_{p0} and k_{i0} are proportional coefficients and integral coefficients at the initial moment, respectively, which are set to 1 and 0.1; Δk_p and Δk_i are increments of scale and integration coefficients, respectively, set to 0.2 and 0.02, respectively.

4 Virtual inertial control based on fuzzy logic control

In order to verify the effectiveness of the grid connection and off-grid control strategies of the compressed air energy storage system and the smooth grid connection strategy of compressed air energy storage based on adaptive PI control, this section establishes the compressed air energy storage grid connection as shown in Figure 4 on the MATLAB/simulink platform. The system model verified the grid-connected and off-grid control strategies of the compressed air energy storage system and the smooth grid-connected strategy of compressed air energy storage based on PI control.

In Figure 4, the rated power of compressed air energy storage is 200 MW, the rated voltage is 13.8 kV; the rated power of transformer T1 is 210MVA, the voltage level is 13.8/35 kV, the load PL1 is 150 MW; the rated power of the grid-side synchronous machine SG is 100 MW. The rated voltage is 13.8 kV; the rated power of transformer T2 is 210MVA, the voltage level is 13.8/35 kV, and the load PL2 is 10 MW. When the system starts, the compressed air energy storage adopts the PI control strategy shown in Figure 3 for pre-synchronization. When the phase angle difference between the compressed air energy storage and the grid side reaches the minimum, the grid is connected, and the compressed air energy storage control mode is switched to V/f control strategy and complete grid connection. The synchronous generator on the grid side adopts V/f control strategy before grid connection and PQ control strategy after grid connection.

Under the premise of the same system, the impulse voltage and current and phase Angle difference synchronization speed under adaptive PI control pre-synchronization and non-adaptive PI control are compared. In order to facilitate comparison, the output waveforms under different working conditions are displayed on the same interface. The compressed air energy

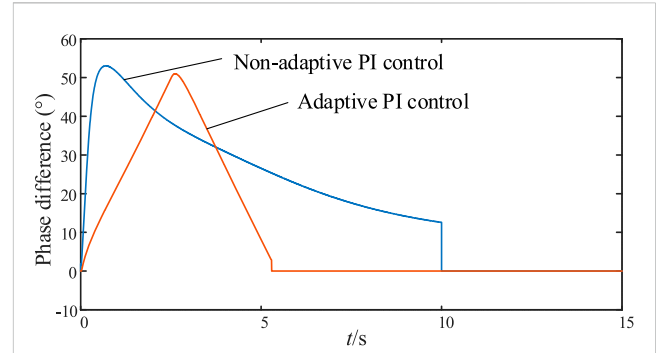


FIGURE 5 Phase difference between compressed air energy storage and power grid.

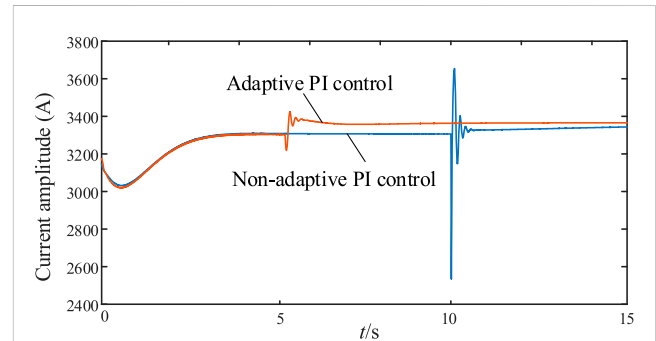


FIGURE 6 Compressed air energy storage grid connection point current amplitude.

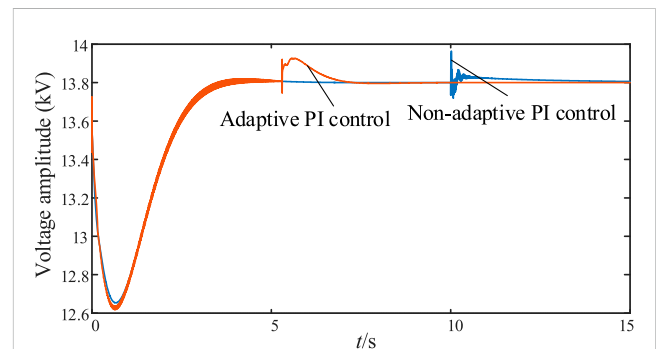
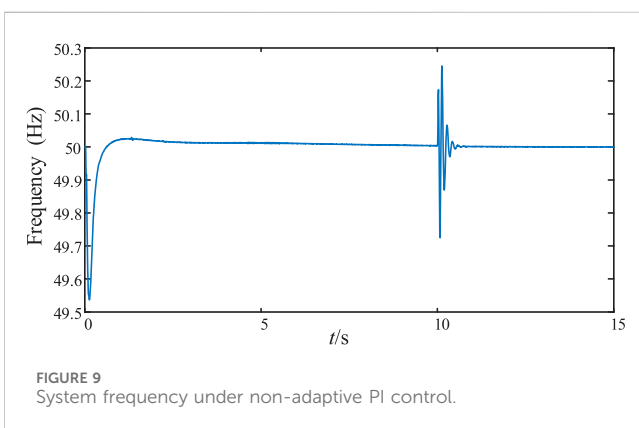
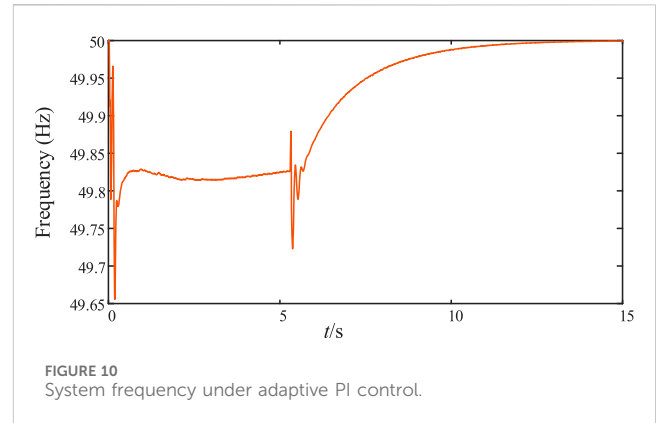
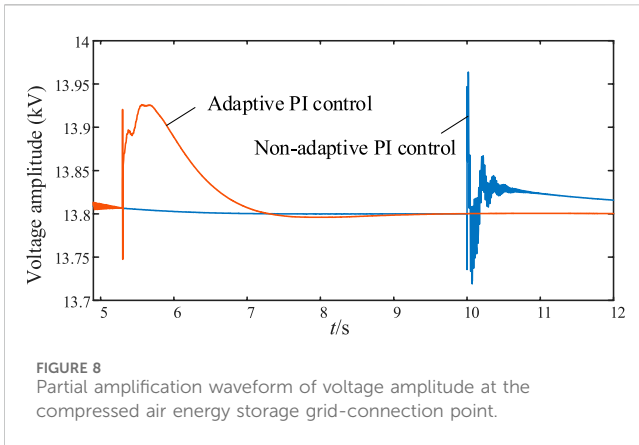


FIGURE 7 Compressed air energy storage grid connection point voltage amplitude.

storage and grid-side phase difference during the pre-synchronization and grid connection processes are shown in Figure 5.

As shown in Figure 5, when adaptive PI control is adopted to reduce the phase difference in the pre-synchronization mode, the phase difference between the compressed air energy storage and the network side will eventually be reduced to 0. The reason why



oscillation amplitude is small, and it takes about 0.6 s from the beginning of grid connection to stability. As for the impulse voltage at the moment of grid connection, it can be seen from the voltage amplitude at the junction point in Figure 7 and the local amplification waveform in Figure 8 that the impulse voltage amplitude under adaptive PI control is smaller, the maximum impulse voltage is about 13.93kV, and the time taken to recover to stability is shorter, during which the voltage does not oscillate. However, the impact voltage amplitude under non-adaptive PI control is larger, and the maximum value of the impact voltage amplitude is about 13.96kV, and the recovery time is longer, and the voltage oscillates more seriously during the recovery.

Figure 9 and Figure 10 show the system frequency under non-adaptive PI control and adaptive PI control respectively. It can be seen from the figure that the system frequency under non-adaptive PI control will have a large oscillation amplitude at the grid-connected time, with the maximum oscillation exceeding 50.2 Hz and the minimum oscillation approaching 49.7 Hz. When adaptive PI control is adopted, the frequency oscillation amplitude of the system is small and there is no overshoot at the grid-connected time, and the maximum frequency is about 49.85 Hz during the oscillation process. It can be seen that the frequency stability is taken into account while the phase Angle synchronization is accelerated.

Based on the experimental results, it can be concluded that the smooth grid-connection strategy proposed in this paper based on adaptive PI control has a good control effect on the reduction rate of phase difference and the suppression of impulse current and voltage during the pre-synchronization process of compressed air energy storage grid-connection, and the voltage, current and frequency have smaller fluctuations when compressed air energy storage is connected to the grid, improving the safe and stable operation ability of the system.

5 Conclusion

Compressed air energy storage has broad application prospects. In order to reduce the impact current and voltage when compressed air energy storage is connected to the power grid and enable smooth grid-connection, this paper proposes a smooth grid-connection

the phase difference of the curve in the figure jumps to 0 is that the grid connection switch is closed at this moment, the compressed air energy storage is connected to the grid, the two run synchronously, and the phase difference becomes 0. By comparison, it can be found that the phase difference of compressed air energy storage and grid side will eventually be reduced to the value that meets the requirements of grid connection when adaptive PI control is used for pre-synchronization and non-adaptive PI control for pre-synchronization. However, the phase difference decreases faster under adaptive PI control, and the phase difference decreases to 0 at about 5.3s. When conventional non-adaptive PI control is adopted, the phase difference stabilizes at 12° at about 10s, and the phase difference reduction speed under adaptive PI control is obviously better than that under conventional PI control.

Figure 6 and Figure 7 show grid-connected current and grid-connected voltage under adaptive PI control and non-adaptive PI control. Due to the difference of grid-connection time between adaptive PI control and non-adaptive PI control, the time of impulse current and impulse voltage will be different. As can be seen from the figure, after grid-connection, the impulse current under non-adaptive PI control is about 3646A, and large amplitude oscillation occurs, and it takes about 1s to reach a stable state from the beginning of grid-connection. The impulse current under adaptive PI control is about 3420A, the

strategy based on adaptive PI control. The conclusions drawn are as follows.

- 1) A smooth grid-connection strategy based on adaptive PI control is proposed, which optimizes the frequency, phase and voltage response characteristics during the pre-synchronization process, reduces the impact current and voltage during compressed air energy storage connecting to power grid, and improves the ability of the system to operate safely.
- 2) Aiming at the problem of smooth grid connection of compressed air energy storage, a pre-synchronization strategy based on adaptive PI control is proposed, which can effectively solved the impact problem caused by mode switching during grid-connection and has good practical engineering application value.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

DW: Data curation, Writing–review and editing. YS: Investigation, Software, Writing–original draft. YG: Project administration, Resources, Writing–review and editing. JL: Methodology, Validation, Writing–review and editing. CY:

Funding acquisition, Resources, Writing–review and editing. JM: Investigation, Writing–review and editing.

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Conflict of interest

Author DW was employed by State Grid Jiangsu Electric Power Company Ltd. Research Institute. Authors YG, JL, and CY were employed by State Grid Jiangsu Electric Power Company Ltd.

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

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