Volatility Control Strategy for Renewable Energy-Based PEM Electrolysis Hydrogen Production System Coupled with Power Grid

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Abstract. This paper studies the volatility control of a renewable energy-based PEM electrolysis hydrogen production system coupled with the power grid. First, the characteristics and sources of volatility in the coupled system are analyzed, and a renewable energy output volatility coefficient model, a PEM electrolyzer dynamic response model, and a system power balance model are constructed. Then, a hierarchical-composite control strategy covering medium-to-long-term, short-term, and real-time timescales is designed. A multi-constraint optimization model is constructed with the core objectives of maximizing renewable energy absorption, minimizing grid volatility, and maximizing hydrogen production efficiency. The optimal control parameters are solved using a particle swarm optimization algorithm. Finally, a simulation platform is built based on MATLAB/Simulink to verify the effectiveness of the strategy under different volatility intensities. The study shows that the proposed control strategy can significantly reduce the voltage/frequency volatility of the power grid, decrease volatility transmission efficiency by 40%-70%, increase renewable energy absorption by 6%-15%, and stabilize hydrogen production efficiency at 78%-82%, effectively ensuring the stable operation of the coupled system and providing technical support for the efficient coupling of renewable energy and the power grid.

Keywords: Renewable Energy, PEM Water Electrolysis for Hydrogen Production, Grid Coupling, Volatility Control, Multi-Objective Optimization.

1. Introduction

In the global energy transition process, renewable energy sources such as wind power and photovoltaics have achieved large-scale development due to their clean and low-carbon characteristics. However, their output is constrained by natural conditions, exhibiting significant volatility and intermittency. Large-scale grid connection poses a severe challenge to grid voltage stability, frequency regulation, and power balance. Data shows that by 2025, the proportion of global renewable energy power generation will exceed 30%, and in some high-penetration areas, the frequency of grid faults caused by fluctuations has increased by 15% year-on-year, restricting the full release of renewable energy consumption potential. PEM water electrolysis for hydrogen production technology has advantages such as fast response speed (millisecond level), wide load regulation range (10%-100% rated power), and high operational flexibility. It can participate in grid regulation as a flexible load, smoothing renewable energy fluctuations by dynamically adjusting hydrogen production power, while simultaneously realizing the conversion and storage of electrical energy into hydrogen energy, constructing a coordinated energy coupling system of "source-grid-load-storage," and providing an effective path to solve the volatility problem.

Existing research largely focuses on single-component modeling or simple control strategy design, which has three shortcomings: first, it does not fully consider the coupling and interaction mechanism between renewable energy, the power grid, and the PEM hydrogen production system; second, the control strategies have a single time scale, making it difficult to adapt to fluctuations of varying intensities; and third, the optimization models do not achieve global coordination of multiple objectives. This paper adopts a technical route of "analyzing coupling characteristics - constructing a control mechanism - designing an optimization strategy - verifying the effectiveness of the strategy," proposing a hierarchical-composite control strategy adaptable to fluctuations at multiple time scales, and establishing a multi-constraint optimization model that balances safety and efficiency, providing theoretical and technical support for improving the operating performance of the coupled system [1].

2. System Characteristics and Control Mechanism Analysis

The core of the renewable energy-based PEM water electrolysis hydrogen production-grid coupled system consists of a renewable energy power generation unit (wind power/photovoltaic), a PEM water electrolysis hydrogen production unit, a grid interface unit, and a monitoring and control unit [2]. The energy flow path is as follows: renewable energy generation prioritizes meeting grid load demand, with surplus electricity input into the PEM electrolyzer for hydrogen production; when renewable energy output is insufficient, the grid supplements power supply to ensure stable operation of the hydrogen production system, achieving bidirectional synergy between "electricity-hydrogen" and "grid-hydrogen production".

System volatility mainly originates from three aspects: First, on the renewable energy side, wind power is affected by random wind speed changes, and photovoltaic power is affected by light intensity and cloud cover interference, exhibiting short-term pulse-like fluctuations and medium-to-long-term trend fluctuations; second, on the grid side, random start-up and shutdown of industrial and residential loads lead to load demand fluctuations, causing voltage and frequency fluctuations; third, on the PEM hydrogen production side, changes in electrochemical characteristics during the current adjustment process of the electrolyzer generate local power fluctuations [3]. To quantify the intensity of fluctuations, the renewable energy output fluctuation coefficient is defined as shown in equation (1):

$$C_{RE} = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(\frac{P_{RE}(t)-\bar{P}_{RE}}{P_{RE}}\right)^2} \tag{1}$$

In the formula, C_{RE} is the renewable energy output fluctuation coefficient, representing the degree of fluctuation; T is the statistical time length (s); $P_{RE}(t)$ is the actual renewable energy output at time t (kW); $\bar{P}_{RE}$ is the average renewable energy output during the statistical period (kW). The larger C_{RE} is, the more severe the fluctuation. When $C_{RE} > 0.2$, control measures need to be initiated to smooth the fluctuation.

A dynamic response model of the PEM electrolyzer is constructed to reflect the dynamic change characteristics of hydrogen production power with input current, as shown in equation (2):

$$\frac{dP_{H_2}(t)}{dt} = k_1 \cdot I(t) - k_2 \cdot P_{H_2}(t) + k_3 \cdot \frac{dI(t)}{dt} \tag{2}$$

In the formula, $P_{H_2}(t)$ is the hydrogen production power at time t (kW); $I(t)$ is the input current of the electrolyzer at time t (A); $k_1$is the current-to-power conversion coefficient (kW/A), which is related to the electrode area and electrolyte conductivity of the electrolyzer; k_2 is the attenuation coefficient (1/s), which characterizes the energy loss inside the electrolyzer; and k_3 is the dynamic adjustment coefficient (kW · s/A), which reflects the influence of the current change rate on the hydrogen production power [4]. This model considers the hysteresis effect of dynamic current changes and is more in line with actual operating characteristics.

The power balance relationship between the power grid and the hydrogen production system is the core of the control mechanism. The power balance model of the coupled system is established as shown in equation (3):

$$P_{RE}(t) + P_{\text{grid}}(t) = P_{\text{load}}(t) + P_{\text{elec}}(t) + P_{\text{loss}}(t) \tag{3}$$

In the formula, $P_{\text{grid}}(t)$ is the interaction power between the power grid and the coupled system at time t (kW), with a positive value indicating that the power grid supplies power to the system and a negative value indicating that the system feeds power to the power grid; $P_{\text{load}}(t)$ is the power load of the power grid at time t (kW); $P_{\text{elec}}(t)$ is the input power of the electrolytic capacitor at time t (kW); and $P_{\text{loss}}(t)$ is the power loss of the system at time t (kW), including line losses, converter losses, etc. By adjusting $P_{\text{elec}}(t)$, the fluctuations of $P_{RE}(t)$ and $P_{\text{load}}(t)$ can be dynamically balanced, maintaining the stability of $P_{\text{grid}}(t)$.

The impact of volatility on the system manifests in three dimensions: First, grid security; voltage fluctuations exceeding ±5% of the rated value or frequency fluctuations exceeding ±0.2" Hz will damage sensitive loads. Second, hydrogen production efficiency; volatility leads to unstable current in the electrolyzer, reducing hydrogen production energy efficiency; when current fluctuations exceed 30%, efficiency can decrease by 8%-12%. Third, energy utilization; volatility increases wind and solar curtailment rates, reducing renewable energy absorption efficiency [5]. Based on these characteristics, the core objective of the control mechanism is to dynamically adjust the hydrogen production load, smooth renewable energy fluctuations, maintain grid parameter stability, and improve the overall system efficiency.

3. Control Strategy Design

A collaborative strategy of "layered control + feedforward-feedback composite control" is designed to achieve precise control of fluctuations of different time scales and intensities based on the coupled system characteristics and control mechanism. Simultaneously, a multi-constraint optimization model is constructed to ensure the feasibility and optimality of the control scheme.

3.1. Construction of a Layered Control Strategy Framework

A layered control framework covering three time scales—medium-to-long-term, short-term, and real-time—is constructed. Each level works in concert to achieve full-time, full-intensity control of fluctuations [6]. The framework structure is shown in Figure 1 below:

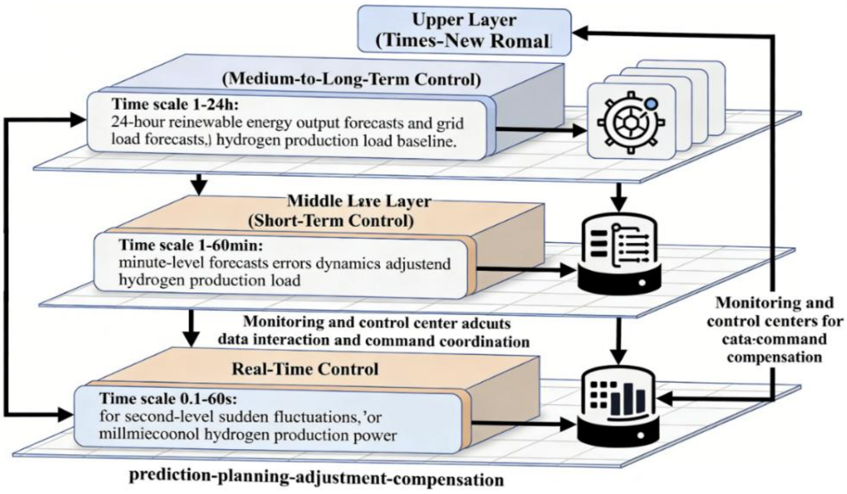

Figure 1. Framework Construction Diagram

- Upper Layer (Medium-to-Long-Term Regulation): Time Scale 1-24h. A hydrogen production load baseline is established to achieve preliminary optimization of energy resource allocation and avoid large-scale power imbalances based on 24h renewable energy output forecasts and grid load forecasts.
- Middle Layer (Short-Term Regulation): Time Scale 1-60min. For minute-level forecast errors, hydrogen production load is dynamically adjusted to smooth out moderate-intensity fluctuations.
- Lower Layer (Real-Time Regulation): Time Scale 0.1-60s. For second-level sudden fluctuations, hydrogen production power is adjusted at the millisecond level to quickly compensate for power gaps and ensure grid parameter stability.

Each level achieves data interaction and command coordination through the monitoring and control center, forming a closed-loop control logic of "prediction-planning-adjustment-compensation".

3.2. Feedforward-Feedback Composite Control Strategy

Combining the predictive nature of feedforward control and the precision of feedback control, a composite control logic is constructed to improve the timeliness and effectiveness of fluctuation control [7]. The feedforward control module, based on the short-term renewable energy output prediction results from the LSTM neural network, optimizes the hydrogen production load allocation scheme 10-30 minutes in advance. When the predicted output fluctuation coefficient $C_{RE} \geq 0.15$, it adjusts the hydrogen production power reserve adjustment margin in advance to avoid the risk of large fluctuations.

The feedback control module collects parameters such as grid voltage (U), frequency (f), actual renewable energy output ($P_{RE}(t)$) and hydrogen production power ($P_{\mathrm{H}_2}(t)$) in real time, and uses a PID control algorithm to dynamically correct the hydrogen production load and compensate for prediction errors. The feedback adjustment amount is defined as shown in equation (4):

$$\Delta P(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(\tau)d\tau + K_d \cdot \frac{de(t)}{dt} \tag{4}$$

In the formula, $\Delta P(t)$ is the hydrogen production power adjustment amount at time t (kW); K_p is the proportional coefficient, K_i is the integral coefficient, and K_d is the derivative coefficient; $e(t)$ is the deviation amount at time t, i.e., the difference between the target grid interaction power and the actual interaction power (kW). By adjusting $\Delta P(t)$, the prediction deviation can be corrected in real time to maintain power balance.

The synergistic mechanism of feedforward and counter-debt is as follows: the feedforward control sets the hydrogen production power adjustment range, and the feedback control performs fine-tuning within this range; when the feedback adjustment amount exceeds the feedforward set range, the feedforward module is triggered to re-optimize the adjustment range, realizing the synergistic cooperation of "coarse adjustment + fine adjustment" to improve the control accuracy and response speed.

3.3. Multi-Constraint Regulation Optimization Model

With the core objectives of maximizing renewable energy absorption rate, minimizing grid fluctuations, and maximizing hydrogen production efficiency, a multi-objective optimization model is constructed, embedding constraints such as technology and resources [8]. The optimal regulation parameters are solved using the Particle Swarm Optimization (PSO) algorithm.

3.3.1. Objective Function Construction

The multi-objective model is transformed into a single-objective optimization using a weighted summation method. The objective function is shown in equation (5):

$$\min F = \omega_1 \cdot (1 - \eta_{RE}) + \omega_2 \cdot C_{\mathrm{grid}} + \omega_3 \cdot \left(1 - \eta_{H_2}\right) \tag{5}$$

In the formula, η_{RE} is the renewable energy absorption rate (%), $\eta_{RE} = \frac{P_{RE,\,\mathrm{nonsumed}}}{P_{RE,\,\mathrm{tota}}} \times 100\%$, $P_{RE,\,\mathrm{consumed}}$ is the absorbed renewable energy power (kW), $P_{RE,\,\mathrm{total}}$ is the total renewable energy output (kW); C_{grid} is the grid fluctuation coefficient, characterizing the combined fluctuation of voltage and frequency, $C_{\mathrm{grid}} = \alpha \cdot \frac{\Delta U}{U_N} + \beta \cdot \frac{\Delta f}{f_N}$, ΔU is the voltage fluctuation (kV), U_N is the rated voltage (kV), Δf is the frequency fluctuation (Hz), f_N is the rated frequency (Hz), α, β are weighting coefficients ($\alpha + \beta = 1$); η_(H_2) is the hydrogen production energy efficiency (%); $\omega_1, \omega_2, \omega_3$ The target weight coefficient ($\omega_1 + \omega_2 + \omega_3 = 1$) can be adjusted according to actual operational needs.

3.3.2. Constraint Embedding

1. PEM Hydrogen Production System Operation Constraints: The input current of the electrolyzer must be within the safe range, $I_{\min} \leq I(t) \leq I_{\max}$, where $I_{\min} = 0.1 I_N$, $I_{\max} = 1.1 I_N$, where I_N is

the rated current (A); the hydrogen production power regulation rate constraint, $\frac{dP_{\text{ele}}(t)}{dt} \leq r_{\max}$, where $r_{\max}$ is the maximum regulation rate (kW/s), with a value of $5-10$ kW/s.

2. Grid Safety Constraints: Voltage fluctuation constraint $\left|\frac{\Delta U}{U_N}\right| \leq 5\%$; frequency fluctuation constraint $\left|\frac{\Delta f}{f_N}\right| \leq 0.2\%$; grid interaction power constraint $P_{\text{grid, min}} \leq P_{\text{grid}}(t) \leq P_{\text{grid, max}}$ to avoid excessive grid capacity utilization.

3. Resource constraints: Water supply constraint $Q_{H_2O}(t) \geq Q_{\min}$, $Q_{H_2O}(t)$ is the water supply flow rate (L/h) at time t, $Q_{\min}$ is the minimum water supply flow rate; Electricity supply constraint $P_{RE}(t) + P_{grid}(t) \geq P_{\text{elec, min,}}$ to ensure the minimum operating power of the hydrogen production system.

3.3.3. Optimization Algorithm Implementation

The PSO algorithm was used to solve the optimization model. The algorithm parameters were set as follows: particle population size 50, number of iterations 100, learning factors $c_1 = c_2 = 2$, and inertia weight w linearly decreasing from 0.9 to 0.4. The optimization variables were the hydrogen production power baseline, PID control parameters (K_p, K_i, K_d), and target weight coefficients [9]. Through iterative algorithm solving, the optimal combination of control parameters under different operating scenarios was obtained, providing data support for the implementation of the control strategy.

4. Simulation Verification and Result Analysis

A coupled system simulation platform was built using MATLAB/Simulink. Different fluctuation intensities and load scenarios were designed to verify the effectiveness and superiority of the proposed control strategy and analyze the impact of key parameters on the control effect.

4.1. Simulation Platform Construction

The simulation platform includes wind power/photovoltaic power generation modules, PEM electrolysis water production hydrogen production modules, grid load modules, converter modules, and control strategy modules [10]. The core parameter settings are as follows: wind power rated power 1000 kW, cut-in wind speed 3" m/s, rated wind speed 12" m/s; photovoltaic rated power 800 kW, module efficiency 22%; PEM electrolyzer rated power 500 kW, rated current 2000 A, adjustment range 10%-100%; grid voltage level 35 kV, rated frequency 50 Hz.

Three test scenarios were designed: Scenario 1 (low volatility): Wind power volatility coefficient $C_{RE} = 0.08$, photovoltaic volatility coefficient $C_{RE} = 0.06$, grid load stable; Scenario 2 (medium volatility): Wind power $C_{RE} = 0.16$, photovoltaic $C_{RE} = 0.12$, grid load volatility 5%; Scenario 3 (high volatility): Wind power $C_{RE} = 0.25$, photovoltaic $C_{RE} = 0.20$, grid load volatility 10%.

4.2. Verification of the effectiveness of the control strategy

4.2.1. Verification of volatility mitigation effect

The grid voltage, frequency volatility amplitude, and renewable energy output volatility transmission efficiency were compared before and after control. The results are shown in Table 1.

Table 1. Comparison of volatility mitigation effect under different scenarios

scene	Regulation Status	Voltage fluctuation amplitude (%)	Frequency fluctuation amplitude (Hz)	Wave propagation efficiency (%)	Renewable energy integration rate (%)
1	No Regulation	2.8	0.15	68	92.3
1	Regulation Regulated	0.9	0.04	22	98.7
2	No Regulation Regulated	4.5	0.28	85	86.5
2	Regulated	1.3	0.07	35	96.2
3	No Regulation Regulated	6.2	0.42	92	78.8
3	Regulated	2.1	0.11	48	93.5

As shown in Table 1, without regulation, the voltage and frequency fluctuation amplitudes increase significantly with increasing fluctuation intensity, and in Scenario 3, the voltage fluctuation exceeds the ±5% safety threshold. After implementing the proposed regulation strategy, the voltage and frequency fluctuation amplitudes in all scenarios are significantly reduced, the fluctuation transmission efficiency decreases by 40%-70%, and the renewable energy absorption rate increases by 6%-15%, indicating that the strategy can effectively mitigate fluctuations and improve energy absorption capacity. The grid voltage fluctuation comparison curves for Scenario 3 are shown in Figure 2.

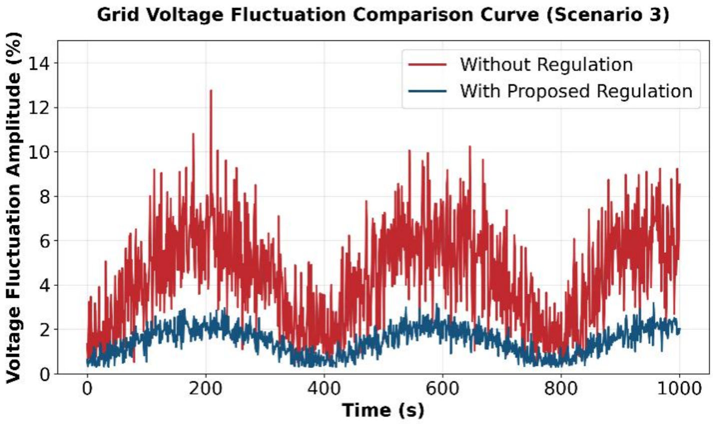

Figure 2. Grid Voltage Fluctuation Comparison Curve (Scenario 3)

The horizontal axis represents time (s), ranging from 0 to 1000 s; the vertical axis represents voltage fluctuation amplitude (%). Curve 1 represents the uncontrolled state, and curve 2 represents the controlled state. It can be seen that the fluctuation amplitude is consistently controlled within 2.1% under controlled conditions, while the maximum fluctuation reaches 6.2% under uncontrolled conditions.

4.2.2. Verification of Efficiency Improvement Effect

The changes in hydrogen production energy efficiency and overall system energy utilization efficiency after the implementation of the control strategy are analyzed, and the results are shown in Figure 3. The horizontal axis represents time (s), ranging from 0 to 1000 s; the vertical axis represents efficiency (%), including hydrogen production energy efficiency (curve 1) and system energy utilization efficiency (curve 2). Under uncontrolled conditions, the hydrogen production efficiency in scenario 3 drops to a minimum of 68%, and the system energy utilization efficiency drops to 72%. After implementing control, the hydrogen production efficiency stabilizes at 78%-82%, and the system energy utilization efficiency stabilizes at 88%-92%, demonstrating a significant efficiency improvement. This is because the control strategy maintains stable operation of the electrolyzer by dynamically adjusting the hydrogen production current, thereby reducing energy loss caused by fluctuations.

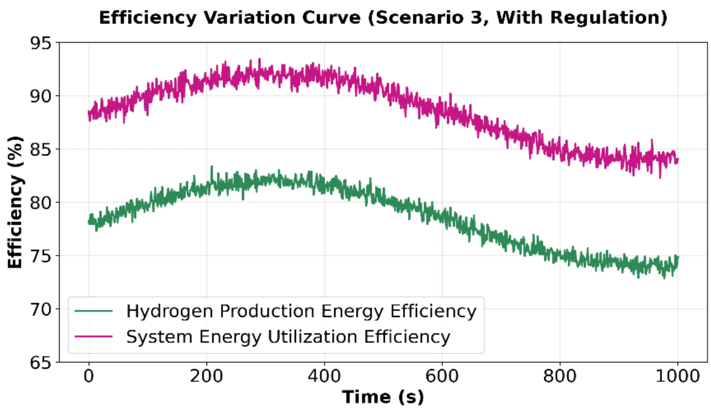

Figure 3. Efficiency Variation Curve (Scenario 3)

4.2.3. System Stability Verification

The stability of the input current and power flow of the PEM hydrogen production system during the regulation process was evaluated. Figure 4 shows the input current fluctuation curve of the electrolyzer in Scenario 2. The horizontal axis represents time (s), ranging from 0 to 1000 s; the vertical axis represents the current fluctuation amplitude (%). Without regulation, the current fluctuation amplitude reached a maximum of 28%, exhibiting significant pulse-like fluctuations. After regulation was implemented, the current fluctuation amplitude was controlled within 8%, significantly improving operational stability. Simultaneously, the power flow fluctuation amplitude decreased from 12% without regulation to below 3%, indicating that the strategy can ensure the stable operation of the coupled system and the power grid.

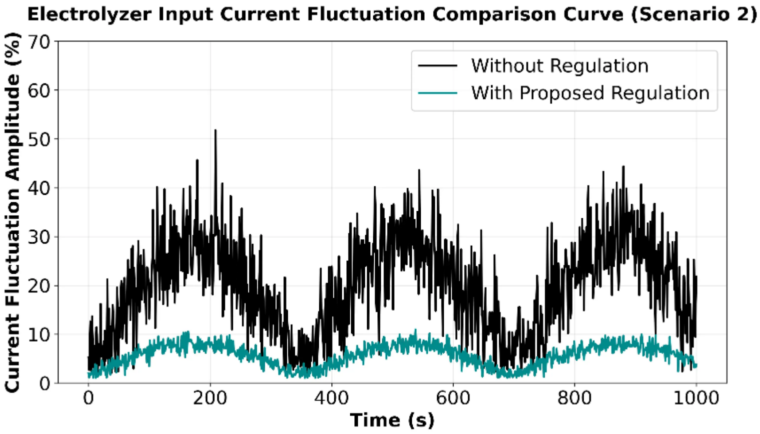

Figure 4. Electrolyzer Input Current Fluctuation Curve (Scenario 2)

4.3. Parameter Sensitivity Analysis

Taking Scenario 2 as an example, the impact of the PID control parameter K_p on fluctuation suppression is analyzed: When K_p increases from 1.0 to 3.0, the voltage fluctuation amplitude decreases from 1.8% to 1.0%, but the faster control response may lead to overshoot; when K_p > 3.0, the overshoot exceeds 1%, and stability decreases. Therefore, the optimal value range for K_p is 2.0–2.5, which balances fluctuation suppression and system stability.

4.4. Strategy Comparison Analysis

Compared with the traditional single feedback control strategy, the proposed hierarchical-composite control strategy in scenario 3 shows a 5.3% increase in renewable energy absorption rate, a 32% reduction in grid fluctuation coefficient, and a 4.8% increase in hydrogen production efficiency. This demonstrates that the proposed strategy has significant advantages in multi-objective optimization and is more suitable for complex fluctuation scenarios.

5. Conclusion

This paper analyzes the characteristics of the PEM water electrolysis hydrogen production-grid coupled system based on renewable energy, clarifies the sources and mechanisms of fluctuations, and constructs a series of core mathematical models. A hierarchical-composite synergistic control strategy is proposed, and a multi-constraint, multi-objective optimization model is established and solved using the particle swarm optimization algorithm. Simulation results show that this strategy can effectively mitigate renewable energy fluctuations of varying intensities, control grid voltage/frequency fluctuations within a safe range, and significantly improve renewable energy absorption rate, hydrogen production efficiency, and system stability. The study has certain limitations, focusing only on the coupling scenario of PEM water electrolysis hydrogen production technology with the grid, without considering the synergistic effects of other energy storage units in a multi-energy complementary system, and without addressing the impact of market mechanisms on the control strategy. Future research can be extended to multi-energy complementary coupling scenarios, integrating energy storage units to further enhance regulation effectiveness. Simultaneously, it can explore optimization of regulation strategies under market mechanisms, promoting the large-scale application and widespread adoption of this technology.

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