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Xiaming Ye, Hongliang Chen, Lijun Ma, Ruyi Qin, Fan Bai and
Jiajie Liu

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Xiaming Ye
State Grid Zhejiang Electric Power Co.,
Ltd. Ningbo Electric Power Supply
Company
Ningbo, China
xiamingye@foxmail.com

Hongliang Chen
College of Electrical Engineering
Zhejiang University
Hangzhou, China
12210028@zju.edu.cn

Lijun Ma
State Grid Zhejiang Electric Power Co.,
Ltd. Ningbo Electric Power Supply
Company
Ningbo, China
13566631391@qq.com

Ruyi Qin
State Grid Zhejiang Electric Power Co.,
Ltd. Ningbo Electric Power Supply
Company
Ningbo, China
659263@qq.com

Fan Bai
Ninghai Yancangshan Electric Power
Construction Co.,LTD
Ningbo, China
21233415@qq.com

Jiajie Liu
Ninghai Yancangshan Electric Power
Construction Co.,LTD
Ningbo, China
1214811834@qq.com

Abstract—In the ever-evolving landscape of the power system, the penetration of wind and solar renewable energy sources into the grid has steadily increased. However, the resulting intermittency of wind and solar power generation poses challenges to the stability of the power system. This paper presents a model for the Hydrogen Capacitor Hybrid Storage System (HC-HSS), comprising a Hydrogen Storage System (HSS) and a Super Capacitor System (SCS). Building upon a detailed modeling of material and energy flows within the HSS, a cost-effective method for mitigating wind and solar power fluctuations is proposed. Additionally, power allocation strategies are developed to accommodate the distinct characteristics of energy storage. The model is solved using a particle swarm optimization algorithm, and case studies demonstrate the effectiveness of the hybrid energy storage configuration and the proposed power allocation strategy.

Keywords—Hydrogen Capacitor Hybrid Storage System, Hydrogen Storage System, Super Capacitor System, Fluctuation Smoothing, Power Allocation Strategy

I. INTRODUCTION

In the context of countries worldwide setting carbon emission reduction targets, the gradual increase in the penetration of wind and solar energy into the grid has been accompanied by advancements in renewable energy utilization technologies. However, the output of wind and solar power generation is characterized by its instability, posing challenges and uncertainties to the power balance of the grid. To address this instability issue, significant research has been conducted both theoretically and practically on energy storage configuration to ensure the security of the grid.

In the field of hybrid energy storage configuration, a substantial number of publications have conducted relevant research. In [1], with the aim of stabilizing the power outputs from distributed power sources and avoiding load shedding, the optimal siting and sizing of hybrid energy storage devices is addressed, considering lithium iron phosphate batteries and supercapacitors. In [2], in the context of microgrids, the complementary energy storage characteristics of high-energy-density storage and high-power-density storage are examined,

specifically with five types of storage considered: lead-acid batteries, NAS batteries, compressed-air energy storage (CAES), flywheel storage, and supercapacitors. The optimization of capacity and cost for constructing hybrid energy storage systems with batteries and supercapacitors in direct current microgrid systems is investigated in [3]. From the perspective of time scales of energy storage response, a planning method is presented in [4] for a three-level hybrid energy storage system, where each level corresponds to intra-day energy transfer, intra-week energy transfer, and intra-year energy transfer, demonstrating the cost superiority of the method through case studies. Additionally, [5-8] have conducted relevant research on hybrid energy storage configuration, most of which focus on addressing the intermittency of wind and solar power generation or the problems caused by this intermittency within the grid.

Most of the existing publications on hybrid energy storage configuration, when categorizing energy storage into power-based and energy-based types, typically focuses on supercapacitors and lithium batteries as the corresponding energy storage options. However, hydrogen storage, as a novel yet significant energy-based storage technology, has received relatively little consideration in the context of hybrid energy storage configuration. Furthermore, existing publications on hybrid energy storage often lack comprehensive control strategies tailored to the distinct characteristics of hybrid energy storage systems. Therefore, these issues continue to hold research significance.

This paper establishes a detailed model for the Hydrogen Storage System (HSS) and the Super Capacitor System (SCS), comprising the Hydrogen Capacitor Hybrid Storage System (HC-HSS). It investigates the configuration of HC-HSS aimed at smoothing the fluctuations in wind and solar power generation. Additionally, corresponding "energy-based" and "power-based" energy storage charging and discharging strategies are proposed. These proposed strategies effectively harness the complementary nature of hybrid energy storage systems. Following the implementation of the hybrid energy storage configuration, it is evident that wind and solar power output becomes significantly smoother and more stable.

II. MODELS

A. Hydrogen Energy Storage Model

The hydrogen storage system consists of the electrolyzer, hydrogen storage tank, compressor, and fuel cell. The hydrogen storage system utilizes the electrolyzer to convert electrical energy into hydrogen gas, which is then compressed and stored in the hydrogen storage tank. The hydrogen gas in the storage tank is subsequently converted back into electrical energy by the fuel cell to provide power to the system.

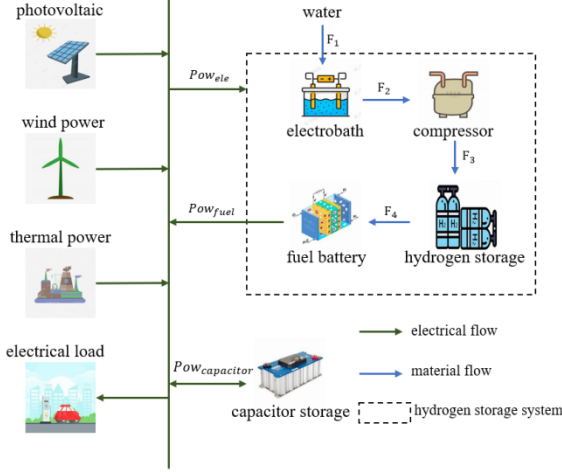


Fig. 1. Schematic diagram of hybrid energy storage system

The electrolyzer electrolyzes water to convert electricity into hydrogen, the hydrogen compressor consumes electricity to store the produced hydrogen into a hydrogen storage tank, and the fuel cell is utilized to convert the hydrogen into electricity when power is required from the hydrogen storage system. The process can be mathematically described by

$$p_{el}^{HSS}(t) = p_{el}^{ELB}(t) + a_1^{HSS} F_2(t) - a_2^{HSS} F_4(t) \quad (1)$$

where $p_{el}^{HSS}(t)$ is the power consumption of the hydrogen storage system, the positive number indicates that the hydrogen storage system absorbs power from the grid, and the negative number indicates that the hydrogen storage system discharges power to the grid; $p_{el}^{ELB}(t)$ is the operating power of the electrolyzer at time t ; a_1^{HSS} is the power consumed by the hydrogen compressor to compress hydrogen per unit mass of hydrogen (3.03 kWh/kg); a_2^{HSS} is the power generation of hydrogen per unit mass of hydrogen for the fuel cell (22.28 kWh/kg); $F_2(t)$ is the hydrogen flow rate from the hydrogen compressor to the storage tank, i.e., the hydrogen flow rate from the electrolyzer; $F_4(t)$ is the hydrogen flow rate from the storage tank to the fuel cell.

Due to the physical and chemical characteristics of the electrolyzer, existing research often employed constant standard energy consumption ratio curves. In reality, the energy consumption ratio follows a nonlinear or linear function. In this paper, a linearized function for the energy consumption ratio is chosen, and the input power to the electrolyzer can be represented as

$$e^{ELB}(t) = e_{max}^{ELB} - [1 - \phi(t)](e_{max}^{ELB} - e_{min}^{ELB}) \quad (2)$$

where $e^{ELB}(t)$ is the power consumption per unit flow rate of the electrolyzer; e_{max}^{ELB} is the power consumption per unit flow rate under full load condition, taken as 55.7 kWh/kg; $\phi(t)$ is the percentage rate of electrolyzer operation; e_{min}^{ELB} is the

power consumption under no load condition, taken as 39.4 kWh/kg.

Material balance calculations reflect the quantitative relationships between material proportions and material transformations in the chemical conversion processes of the system. The material balance equation for the hydrogen storage process is given by:

$$F_1(t) = \frac{M_{W.H_2O}}{M_{W.H_2}} F_2(t) \quad (3)$$

$$F_2(t) = \frac{x_{el}^{ELY}(t)}{e^{ELY}(t)} \quad (4)$$

$$F_2(t) = F_3(t) \quad (5)$$

where $F_1(t)$ represents the flow rate of water electrolyzed in the electrolyzer; $M_{W.H_2O}$ and $M_{W.H_2}$ are the molecular molar masses of water and hydrogen, which are 18g/mol and 2g/mol respectively; and $F_2(t)$ represents the flow rate of hydrogen gas after compression by the hydrogen compressor, neglecting hydrogen loss throughout the entire process. An operational model for the hydrogen storage system is established, representing the sequential relationship of the hydrogen storage tank's capacity between two consecutive time intervals:

$$L^{HS}(t) = L^{HS}(t-1) + F_3(t) - F_4(t) \quad (6)$$

where $L^{HS}(t)$ represents the amount of hydrogen stored in the hydrogen storage tank at time t .

The total annualized investment cost of the hydrogen energy storage system can be calculated by

$$C_{HSS} = \sum_{k=1}^3 C_{cap,k} \cdot \frac{r(1+r)^m}{(1+r)^m - 1} \quad (7)$$

where r denotes the discount rate and m denotes the operating life of the system, which is taken as 20 years. $C_{cap,k}$ ($k = 1, 2, 3$) denotes the investment cost of the electrolyzer, fuel cell, and hydrogen storage device, respectively, calculated as follows:

$$\begin{cases} C_{cap,1} = C_H \cdot \lambda_{H_1} \\ C_{cap,2} = C_F \cdot \lambda_{H_2} \\ C_{cap,3} = E_H \cdot \lambda_{H_3} \end{cases} \quad (8)$$

where C_H and λ_{H_1} respectively represent the installed capacity and unit installed investment cost of the electrolyzer, with λ_{H_1} set at 900 yuan/kW; C_F and λ_{H_2} respectively represent the installed capacity and unit installed investment cost of the fuel cell, with λ_{H_2} set at 100 yuan/kg; E_H and λ_{H_3} respectively represent the capacity of hydrogen storage device and unit capacity investment cost, with λ_{H_3} set at 430 yuan/kW.

B. Supercapacitor Model

The total nominal energy of the supercapacitor bank E_n can be attained by

$$E_n = 0.5nC_{scs}U_c^2 \quad (9)$$

where C_{scs} denotes the capacitance value of an individual supercapacitor module, U_c stands for the terminal voltage, and n represents the quantity of supercapacitor modules per unit.

The annualized configuration cost of the supercapacitor component can be calculated by

$$C_{scs} = C_e + C_p \quad (10)$$

$$C_e = \frac{r(1+r)^m}{(1+r)^m - 1} m_e E \quad (11)$$

$$C_p = \frac{r(1+r)^m}{(1+r)^m - 1} m_p P \quad (12)$$

where C_e and C_p represent the capacity and power costs of the supercapacitor energy storage system, respectively; m_e represents the cost per unit energy storage capacity, set at 1600 yuan/kWh, while m_p represents the cost per unit power capacity, set at 2400 yuan/kW.

III. CONFIGURATION MODEL

A. Objective Function

To mitigate the fluctuations in wind and solar power generation, the transmission grid-primarily focuses on addressing the high-frequency variations associated with these renewable sources. Consequently, it is possible to decompose the wind and solar power output into two distinct components: the continuous component and the high-frequency fluctuation component, for analytical purposes within the academic context.

In this work, we consider "minute-level" fluctuations as high-frequency variations and, as such, primarily focus on mitigating these minute-level fluctuations. The methodology employed for mitigating fluctuations relies on a sliding average approach, where the average power values before and after a given sampling instant are used to determine the smoothing target power for that specific moment, representing the continuous component of wind and solar power. In the transmission grid, assuming a sampling period of T , the sliding average is computed using M consecutive sampling points centered around time t :

$$P_{pvw}(t) = P_{pv}(t) + P_w(t) \quad (13)$$

$$P_{obj} = \frac{1}{2M+1} P_{pvw}(t+M) + P_{pvw}(t+M-1) + \dots + P_{pvw}(t) + \dots + P_{pvw}(t-M+1) + P_{pvw}(t-M) \quad (14)$$

$$P_{left}(t) = P_{pvw}(t) - P_{base}(t) \quad (15)$$

where $P_{pvw}(t)$ is the output power value of wind and solar power at moment t ; P_{obj} is the time t target output power for the electric grid system, calculated using the sliding average method, and it represents the continuous component of wind and solar power, which serves as the output power target for the grid system; $P_{left}(t)$ is the additive variation to the continuous component, signifying the target compensation power from the hybrid energy storage system. All values are in kilowatts (kW).

The evaluation function of the wind and light fluctuation smoothing effect is:

$$f_{tech} = \frac{\sum_{t=1}^T [P_{cp}(t) - P_{base}(t)]^2}{T} \quad (16)$$

where $P_{cp}(t)$ is the total output power of the system after energy storage compensation.

When configuring hybrid energy storage to mitigate fluctuations in renewable energy output, it is essential to consider cost-effectiveness. Therefore, in order to balance

both configuration costs and technical objectives, an objective function is formulated as

$$\min f = \text{ratio}_{cost} \cdot (C_{HSS} + C_{scs}) + \text{ratio}_{tech} \cdot f_{tech} \quad (17)$$

B. Operational Constraints

(1) Hydrogen storage systems

The state of charge (SOC) of the hydrogen storage tank is defined to ensure the safe operation and longevity of the energy storage system. The SOC of the hydrogen storage tank needs to be maintained within specific constraints. In addition to meeting SOC constraints, hydrogen storage must also satisfy constraints on maximum storage capacity, maximum hydrogen flow rate, and fuel cell's maximum hydrogen consumption rate:

$$\begin{cases} S_{OC}^{HS}(t) = \frac{L^{HS}(t)}{L_{max}^{HS}} \\ S_{OC,min}^{HS} \leq S_{OC}^{HS}(t) \leq S_{OC,max}^{HS} \\ 0 \leq F_2(t) \leq F_{2,max} \\ 0 \leq F_4(t) \leq F_{4,max} \end{cases} \quad (18)$$

where $S_{OC}^{HS}(t)$ represents the state of charge (SOC) of the hydrogen energy storage system at time t ; $S_{OC,min}^{HS}$ and $S_{OC,max}^{HS}$ respectively denote the minimum and maximum SOC limits for the hydrogen energy storage system, set at 0.1 and 0.9; $L^{HS}(t)$ represents the hydrogen mass in the storage tank at time t , and L_{max}^{HS} is the capacity of the hydrogen storage tank; $F_{2,max}$ represents the upper limit of hydrogen mass compression by the hydrogen compression equipment per unit time, and $F_{4,max}$ represents the upper limit of hydrogen mass supplied from the storage tank to the fuel cell per unit time.

(2) Capacitor system

The operation of the energy storage system needs to satisfy the output power limit as well as the SOC constraints:

$$-Cap_{capacitor} \leq Pow_{capacitor}(t) \leq Cap_{capacitor} \quad (19)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (20)$$

C. Power Allocation Strategy

In the hybrid energy storage configuration presented in this study, the energy allocation strategy for the two types of energy storage can be summarized as follows: It maximizes the complementary characteristics of both energy storage types. The energy-based storage serves as the primary energy storage system, while the power-based storage acts as the secondary energy storage system. Together, they are employed to smooth the wind and solar power output within the transmission network.

Considering the characteristics of the two energy storage types and their respective roles, the overall energy management strategy should adhere to the following principles:

(1) Energy-based storage responds to the fundamental power component, which comprises the low-frequency portion of the power differential.

(2) Power-based storage responds to frequent power fluctuations, encompassing the high-frequency portion of the power differential.

In line with the fundamental principles mentioned above, the energy-based energy storage system avoids frequent startups and operates in an optimized state, thus effectively extending its lifespan. Conversely, the power-based energy storage system fully leverages its rapid response capabilities to achieve real-time compensation for power differentials, thereby enhancing the stability of the power system and the overall cost-effectiveness of the energy storage system.

The specific charging and discharging strategy is illustrated in the following flowchart:

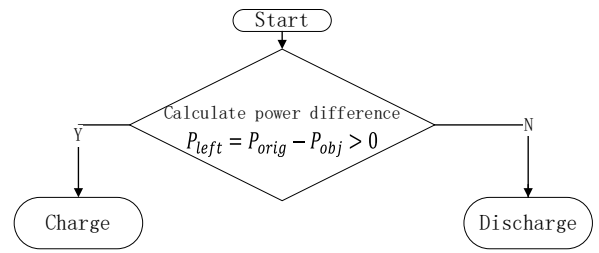


Fig. 2. Judgement basis of charging and discharging strategy

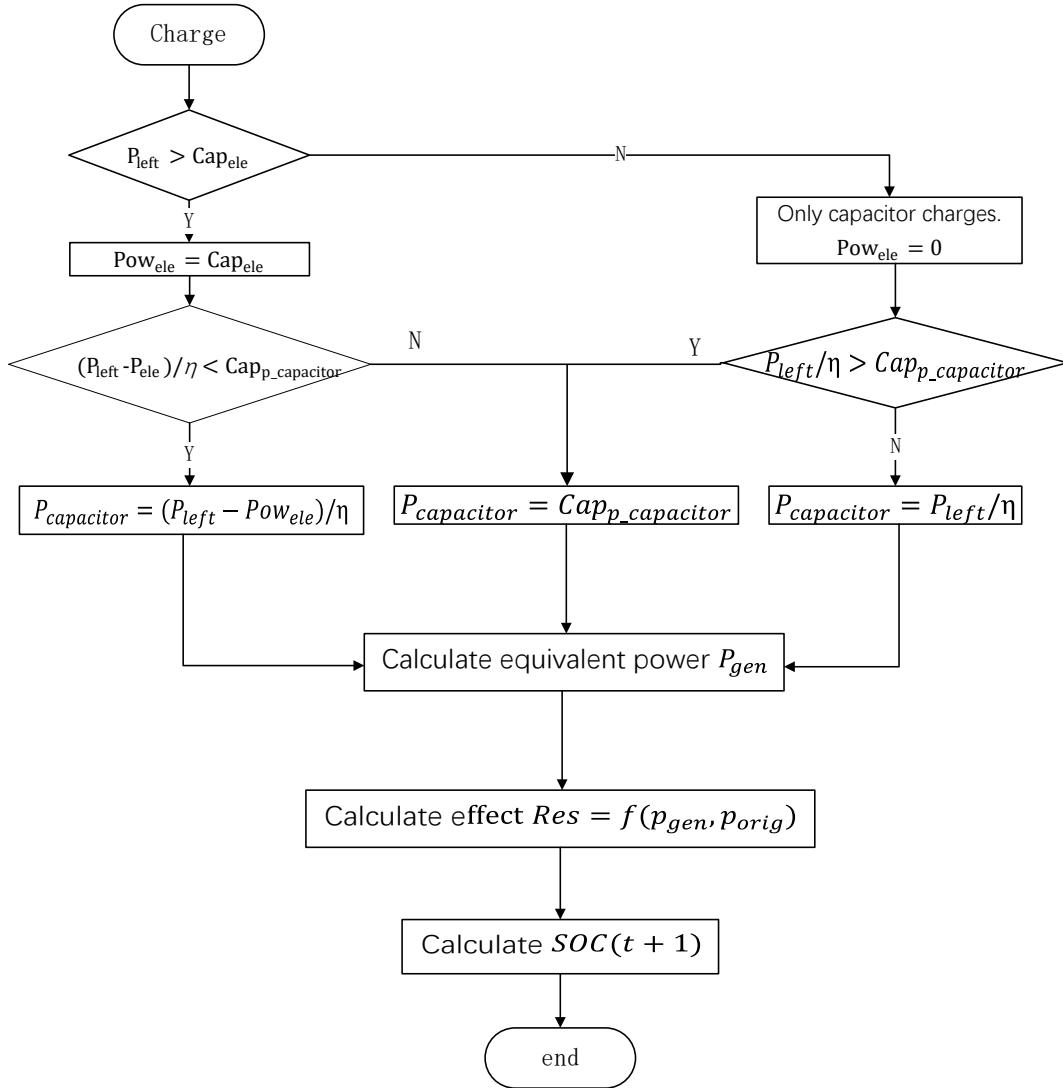


Fig. 3. Strategy of charging

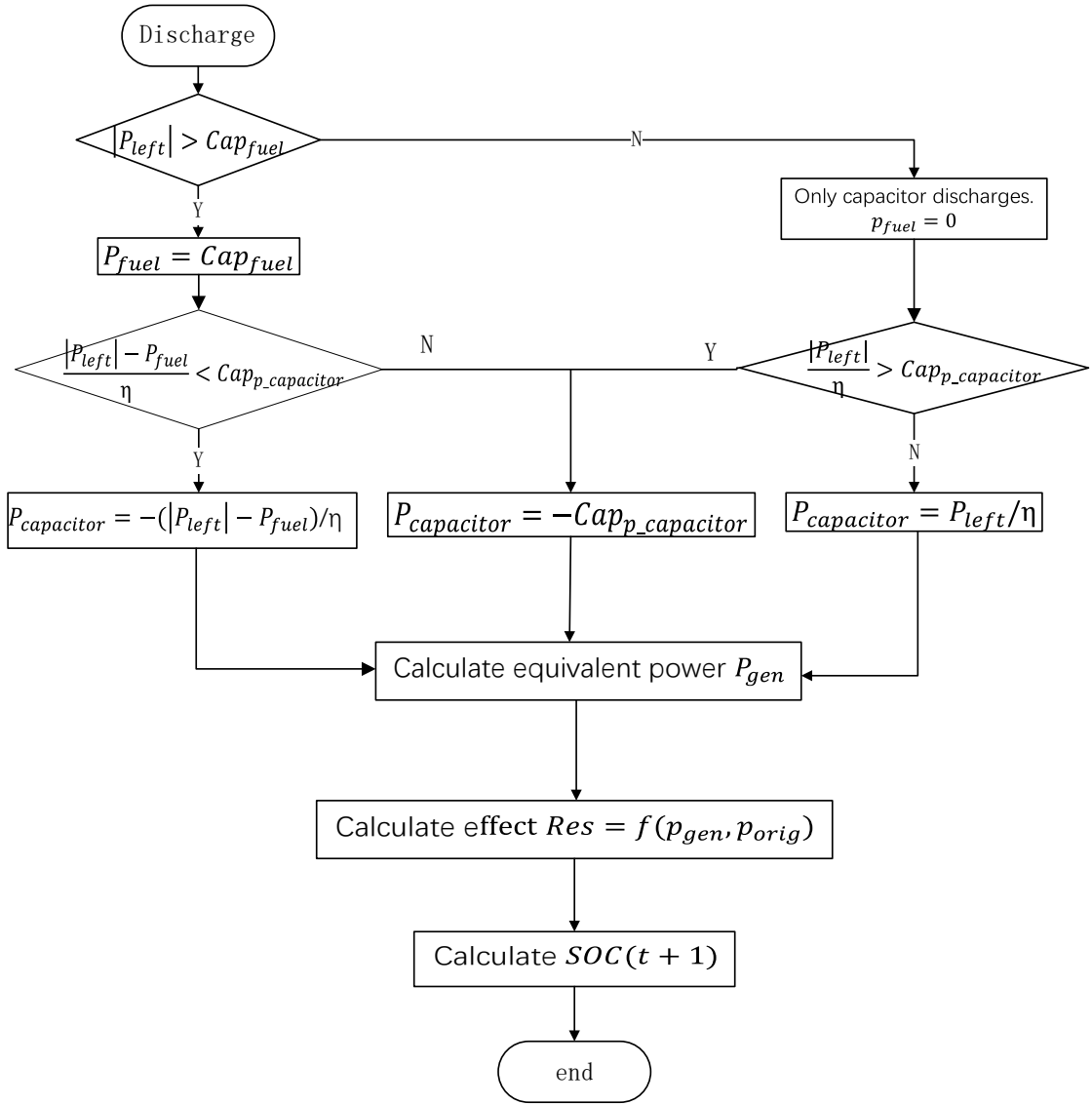


Fig. 4.Strategy of discharging

IV. CASE STUDY

A case study was conducted for validation purposes. Typical output curves for wind and solar power for one week in a specific region were selected, as shown in the Fig.5. The objective of the configuration is to smooth the local renewable energy output curve.

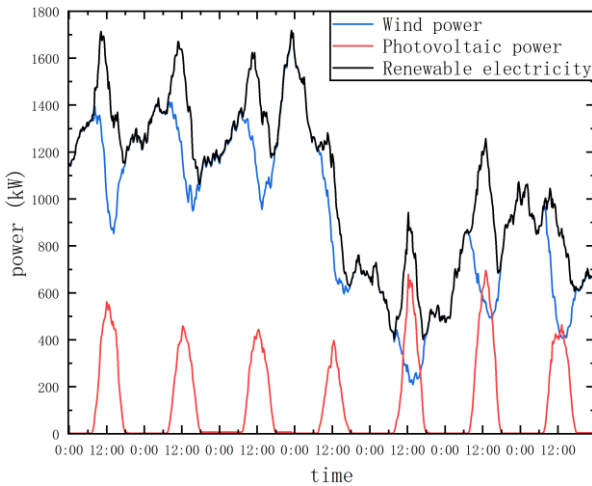


Fig. 5.Local wind and renewable energy output curves

Utilizing the aforementioned power allocation strategy, the configuration of the HC-HSS was conducted, and a particle swarm optimization algorithm was employed for the solution. The results of the hybrid energy storage configuration capacity are as follows:

TABLE I.HYBRID ENERGY STORAGE CONFIGURATION CAPACITY RESULTS

Hydrogen Storage System		Super Capacitor System		
Electrolyte(kW)	Hydrogen storage (kg)	Fuel battery (kW)	Energy capacit (kWh)	Power capacit (kW)
24.1	39.3	21.1	17.1	13.7

The annualized cost for the SCS configuration is 5236 yuan, while the annualized cost for the HSS configuration is 3020 yuan. The optimization of technical indicators resulted in a value of 39.5.

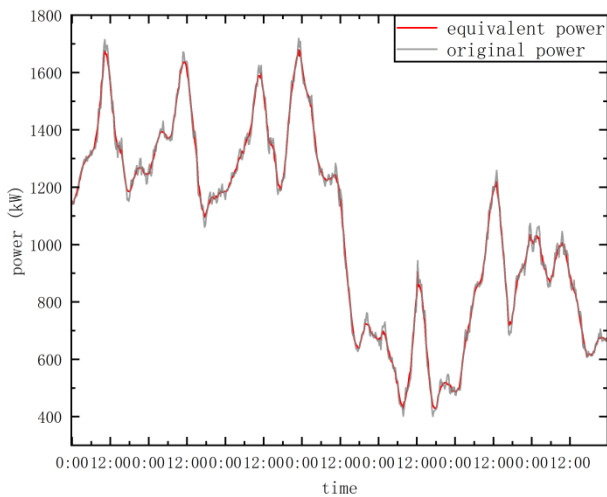


Fig. 6. Smoothing effect of a typical week's wind and photovoltaic output curve in a region

Figure 6 depicts the smoothing effect on the typical one-week wind and solar power output curves in the region. It is evident that the configuration of hybrid energy storage has significantly smoothed the output of renewable energy sources, enhancing the stability of renewable energy generation.

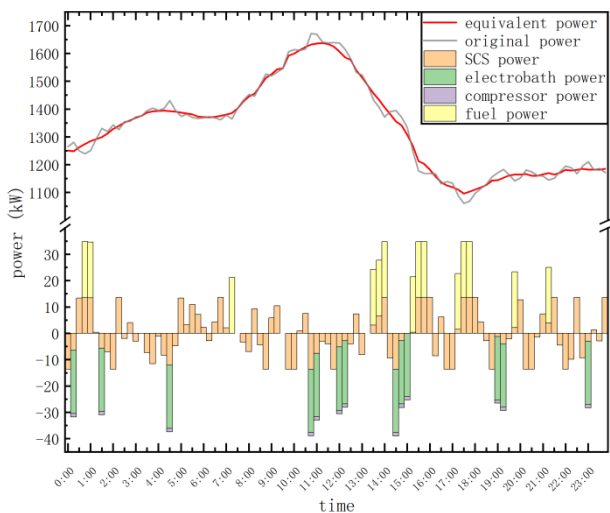


Fig. 7. HC-HSS output profile and smoothing effect on wind and renewable energy outputs

A typical day within a typical week was selected to illustrate the output of the HC-HSS and its smoothing effect on wind and solar renewable energy generation, as shown in the graph above. From the simulation results, it is evident that the HC-HSS, composed of both HSS and SCS components, has effectively coordinated to smooth the output of renewable energy sources, jointly smoothing the renewable energy output.

HSS and SCS respectively represent energy-based and power-based energy storage, and play distinct roles in smoothing the output of wind and solar renewable energy sources. HSS comes into play only when there is a significant shortage of power, serving as an energy-based support. Therefore, HSS has fewer startup instances, which is advantageous for achieving its expected operational lifespan. On the other hand, SCS starts frequently, aligning with its role as power-based energy storage.

CONCLUDING REMARKS

Major contributions of this work could be summarized as following:

(1) Mathematical models are established for HSS and SCS. In the HSS model, a detailed description of the electrolyzer, compressor, hydrogen storage tank, and fuel cell is provided, covering both energy and material flows.

(2) A power allocation method is presented for the hybrid energy storage system HC-HSS. This power allocation method prioritizes the activation of SCS when there is a power deficit, and when the power deficit is substantial, it activates HSS to provide energy-based support. The proposed power allocation method effectively leverages the inherent characteristics of energy-based and power-based energy storage, ensuring that energy-based storage has fewer startup instances, thereby prolonging its operational lifespan.

(3) The configuration method for HC-HSS presented in our work balances configuration costs and technical indicators. After the configuration of HC-HSS, it demonstrates improved smoothing of wind and solar renewable energy output.

Areas for further research in the future include:

(1) In this work, it is assumed that the energy-based energy storage system HSS has fewer startup instances, which is beneficial for extending its operational lifespan. Future research should delve deeper into the impact of HSS's operational behavior on its lifespan and refine the characteristics related to the lifespan of energy-based energy storage.

(2) The hybrid energy storage system explored in this paper primarily focuses on smoothing the output of wind and solar renewable energy sources. Our future research will investigate the broader applications of hybrid energy storage, including its potential roles in peak shaving, frequency regulation, and other functions.

(3) In the scenario considerations presented in this work, the aspect of load demand is not taken into account. Future research will incorporate load considerations and include responsive load demand within the model.

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