Optimization Scheduling Method of Solar Photovoltaic and Fuel Cell Combined Power Generation System

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Abstract

The performance of the battery used in the traditional solar photovoltaic power generation system is poor, and the solar energy has a certain volatility, which makes the performance of the solar photovoltaic power generation system decline significantly. In order to improve the performance of the solar photovoltaic power generation system, a solar photovoltaic fuel cell combined power generation system has been developed. However, there are some problems in the process of traditional combined generation system optimal scheduling, such as high investment cost and total cost, and short generation time of optimal scheduling scheme. This paper takes solving the problems of

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traditional system optimal scheduling as the research goal, a new optimization scheduling method of solar photovoltaic and fuel cell combined power generation system was designed. The composition and topological structure of the solar photovoltaic fuel cell combined power generation system are analyzed. The system is composed of photovoltaic array, fuel cell, electrolytic cell, short-term energy storage unit and energy control unit. It can mainly convert sunlight radiation into electric energy, and convert it into DC or AC used by people through multiple links, so as to ensure the stability and security of power supply in our country. A scheduling model is established according to the photovoltaic cell power generation model, the fuel cell power generation model, the electrolytic hydrogen production model, the battery model, the power conversion model and the combined power generation system model. And the multi-objective cuckoo algorithm is used to solve the model, the optimization scheduling results of solar photovoltaic fuel cell combined power generation system are obtained. The experimental results show that the total investment cost of this method is reduced by 123678.4 yuan and 175858.7 yuan compared with the experimental comparison method, and the total cost is reduced by 301195.5 yuan and 414991.8 yuan compared with the experimental comparison method. It shows that compared with the experimental comparison method, the total investment cost and total cost of this method are lower, and the generation time of the optimal scheduling scheme is between 0.19s and 0.25s, and the practical application effect is good. It fully solves the problems existing in the traditional methods and has certain application significance.

Keywords: Solar photovoltaic, fuel cell, combined power generation system, optimization scheduling, multi-objective cuckoo algorithm.

1 Introduction

The current stage, the relationship between the environment and energy problem has received the widespread attention of the society, and energy problem has been threatening human survival and development, it represented by the fossil fuel energy has been consumed, and the generated in the process of combustion air pollution a serious threat to the atmospheric environmental quality, frequent cause of ecological environment problems, it poses a serious threat to people's health [1]. The greenhouse gases produced by human activities mainly come from the production and utilization of energy. These greenhouse gases have begun to have a significant impact on the global climate. The existing fossil fuels are non renewable resources, especially oil and gas resources, which will face the problem of exploitation depletion, resulting in the increasingly prominent contradiction between resources and development. Nowadays, people are paying increasing attention to the ecological environment and increasing investment in research and development, which promotes the birth and development of new energy industry. The special focus of high-tech industrialization of renewable energy and new energy includes five fields, including hydrogen energy and solar energy. In the field of hydrogen energy, the special focus is on the production and storage of hydrogen fuel, and the industrialization of special fuel cells. In particular, solar photovoltaic, as one of the clean energy sources, has attracted wide attention from all countries [2, 3]. But because the traditional solar photovoltaic power generation system using battery performance is poorer, and solar energy have certain volatility, make solar photovoltaic power generation system performance dropped substantially, therefore the promotion solar photovoltaic power generation system performance, research and development of the solar energy photovoltaic power generation system of fuel cell, in order to improve system comprehensive performance, promote the further development of photovoltaic power generation field.

Most of the research results in other fields are just transferred to the optimization scheduling of solar photovoltaic fuel cell combined power generation system. For example, reference [4] proposes an optimization scheduling method of solar thermal photovoltaic combined power generation system based on improved PSO algorithm. Aiming at the important problem of optimization scheduling of combined power generation system, an optimization scheduling control architecture of solar thermal photovoltaic combined power generation system is designed. The reactive power of the system is determined by collecting the bus voltage of the system, and the system optimization scheduling model is built. The optimization scheduling model is solved by using the improved PSO algorithm, and the optimization scheduling results of solar thermal photovoltaic combined power generation system are obtained. However, when this method is applied to the research field of optimization scheduling of solar photovoltaic fuel cell combined power generation system, the scheduling method is less economical and the practical application effect is not good. Reference [5] proposes an optimization scheduling method for the optimal dispatching of wind light storage fire combined power generation system. According to the characteristics of combined power generation system, this method sets up multiple optimization objectives to build relevant dispatching models, and uses a variety of algorithms to optimize the model to achieve the optimal dispatching of the system. However, when the method is applied to the research field of optimization scheduling of solar photovoltaic fuel cell combined power generation system, it is found that the applicability of the method is long, resulting in a long generation time of scheduling schemes and reduced overall scheduling efficiency.

In order to solve the problems existing in the traditional optimal scheduling method of combined power generation system, a new optimization scheduling method of solar photovoltaic and fuel cell combined power generation system is designed, and the application effect in the process of optimal scheduling of combined power generation system is verified by experiments.

2 Design of Optimization Scheduling Method of Solar Photovoltaic and Fuel Cell Combined Power Generation System

2.1 Combined Solar Photovoltaic and Fuel Cell Power Generation System

The system structure is shown in Figure 1.

The system is composed of photovoltaic array [6, 7], fuel cell, electrolytic cell, short-term energy storage unit and energy control unit, etc., which can mainly convert solar radiation into electric energy and convert it into DC

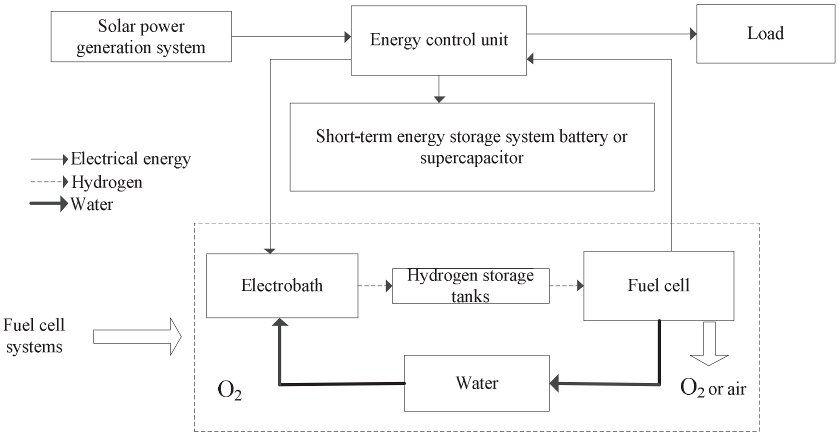

Figure 1 Structure of solar photovoltaic and fuel cell combined power generation system.

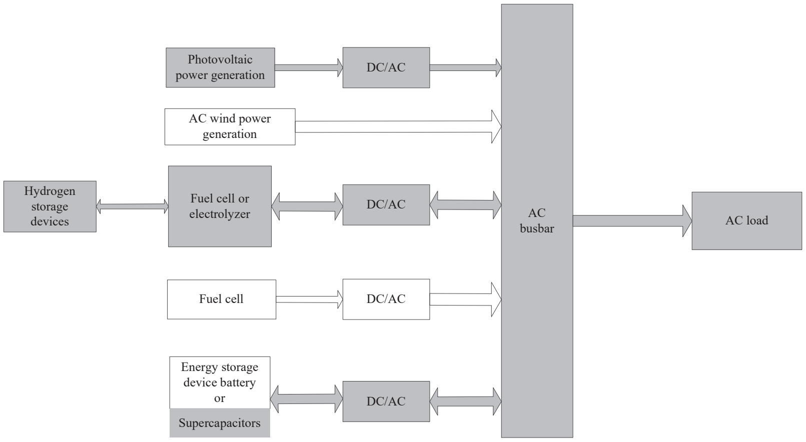

Figure 2 AC bus topology.

or AC electricity for human use through multiple links, so as to ensure the stability and safety of power supply.

The AC bus and DC bus topology of the system are as follows:

(1) AC bus topology

Different power generation units are connected to the AC bus in the form of AC [8] and directly supply power to the AC load. The topology of the AC bus is shown in Figure 2.

The main feature of ac bus topology is that the capacity expansion of the system is relatively easy to achieve, and the control system of the whole system does not need to be changed when the components of the system are changed [9, 10].

(2) DC bus topology

Different power generation units are connected to the public bus in the form of DC, through which the bus supplies power to the DC load and ac users [11, 12]. The topology of the DC bus is shown in Figure 3.

The main characteristic of dc bus topology is that it can continuously meet the power demand of the load. The topology design of combined power generation system is relatively easy to implement. Limited by the rated capacity of DC/AC inverter in the system [13, 14], it will be very complicated to add new electric energy storage devices to improve the capacity of the hybrid system.

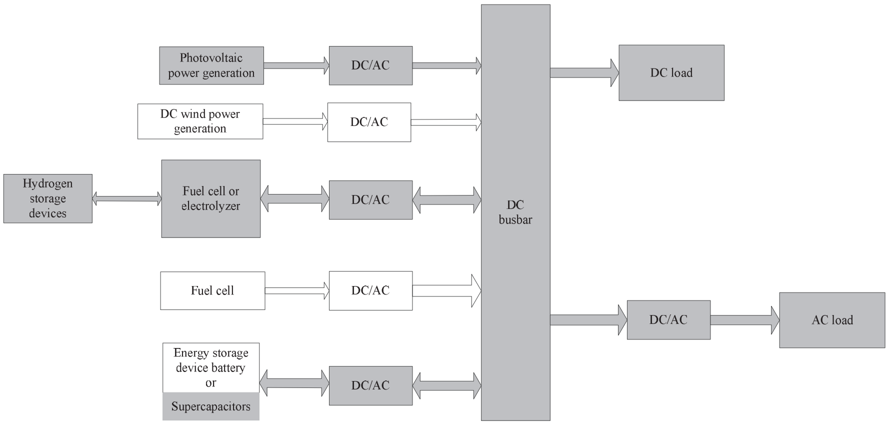

Figure 3 Topology of DC bus.

2.2 Mathematical Model Construction

Mathematical model is the basis for optimization scheduling design of combined power generation system. Therefore, relevant mathematical models are constructed for different components of solar photovoltaic and system to ensure subsequent optimization scheduling effect.

(1) photovoltaic cell power generation model

Under the light intensity of 1 kW/m^2 and the operating temperature of 25°C, the relationship between the output voltage and current of photovoltaic cells in the solar photovoltaic and fuel cell combined power generation system can be expressed as:

$$I = I_{SC}\{1 - K_1[\exp(K_2 V^m - 1)]\} \tag{1}$$

In the above formula, K_1, K_2 represents the change coefficient of voltage and current, I is electric current I_{SC} is the short-circuit current, and V^m is the battery voltage under standard conditions [15]. Its output voltage V_{cell} and current I_{cell} are calculated by the following formula:

$$I_{cell} = I + \alpha\left(\frac{G}{G_0}\right)\Delta T_c + \left(\frac{G}{G_0} - 1\right) I_{SC} \tag{2}$$

$$V_{cell} = V + \beta\Delta T_c + R_S(I_{cell} - I) \tag{3}$$

In the above formula, α and β are different temperature coefficients, G_0 and G respectively represent the lowest value and the highest value of illumination intensity, and ΔT_c represents the temperature change value. The calculation formula is as follows:

$$\Delta T_c = T_a + \frac{G}{800}(N_O - T_a') \tag{4}$$

In the above formula, N_O represents the standard test temperature and T_a' represents the standard temperature.

The specific description of photovoltaic cell generation model is as follows:

$$P_1 = \frac{\Delta T_c(\alpha + \beta)}{K_1 + K_2} \tag{5}$$

(2) Fuel cell model

At the anode of the battery, the fuel cell oxygen molecules are ionized into oxygen ions and electrons [16], and the reaction equation is:

$$H_2 \rightarrow 2H^+ + 2e^- + Heat \tag{6}$$

The cathode equation is described as follows:

$$\frac{1}{2}Q_2 + 2H^+ + 2e^- \rightarrow H_2O + Heat \tag{7}$$

In this way, electrical energy E_0 is generated. Therefore, under certain operating conditions, as long as fuel gas H_2 and oxidizer gas O_2 are continuously supplied, direct current can be continuously generated. The total chemical equation is as follows:

$$\frac{1}{2}Q_2 + H_2 \rightarrow H_2O + Q_0 + E_0 \tag{8}$$

In the formula above, Q_0 is heat. The fuel cell model is as follows:

$$P_2 = \frac{E_0 + Q_0}{Q_2} \tag{9}$$

(3) Hydrogen production model of electrolyser

In the electrolytic cell, water can be separated and decomposed into hydrogen and oxygen through electrolyte. The electrochemical reaction of water electrolysis is as follows:

$$H_2O(I) + E_0 \Rightarrow H_2(g) + 0.5O_2(g) \tag{10}$$

Faraday current efficiency calculation formula is as follows:

$$\mu_F = 96.5 \exp\left(\frac{0.09}{i_e}, \frac{75.5}{i_e^2}\right) \tag{11}$$

Where, i_e is the current in the electrolytic device.

The specific description of hydrogen production model of electrolyser is as follows:

$$P_3 = \frac{\mu_F i_e N_C}{2F} \tag{12}$$

In the above formula, N_C is the number of electrolyzer.

(4) Battery model

The specific components of the battery charging and discharging model are as follows:

$$P_4 = SOC(t)(1 - D_s) + K(V_B I - R_0 I_2) \tag{13}$$

Where, $SOC(t)$ is the capacity of the battery at moment t, D_s and K are the discharge quantity and discharge efficiency respectively, V_B is the voltage of the battery, R_0 represents the internal resistance of the battery, and I, I_2 represents the current at different moments respectively.

(5) Power conversion model

The circuit of solar photovoltaic fuel cell combined power generation system works in continuous conduction mode, and the following formula holds.

$$D_c = \frac{t_{on}}{T_s} \tag{14}$$

In the above formula, D_c represents duty cycle, t_{on} and T_s represent conduction time and conduction period respectively.

The converter U_0 is calculated by the following formula:

$$U_0 = U_s \times D_c \tag{15}$$

In the above formula, U_s represents the input voltage of the converter.

The calculation formulas of energy storage inductance L, ripple voltage ΔU_0 and output filter capacitance C are as follows:

$$L = \frac{(1 - D_c) R T_s}{2} \tag{16}$$

$$\Delta U_0 = \frac{U_0(1-D_c)}{8LC} Ts^2 \tag{17}$$

$$C = \frac{U_0(1-D_c)}{8L\Delta U_0} Ts^2 \tag{18}$$

The power conversion model is described as follows:

$$P_5 = \frac{L \times \Delta U_0 \times C}{D_c} \tag{19}$$

(6) Scheduling model

The scheduling model of solar photovoltaic fuel cell combined power generation system is described as follows:

$$P_{PV} = \sum_{i=1}^{n} (p_i + t_i + z_i) \tag{20}$$

Where, t_i is the total operating cost of the combined power generation system and z_i represents the PV consumption.

2.3 Model Solution Based on Multi-objective Cuckoo Algorithm

Based on the constructed scheduling model, the multi-objective cuckoo algorithm is used to optimize and solve the model, and the solution result is the optimization scheduling result of the system.

The cuckoo position is calculated by the following formula:

$$x_i^{(t+1)} = x_i^t + \partial \oplus L(\lambda) \tag{21}$$

In the above formula, $x_i^{(t+1)}$ represents an individual i in generation $t+1$, x_i^t represents an individual i in generation t, and $L(\lambda)$ represents a random search path. The calculation formula of step size control quantity ∂ is as follows:

$$\partial = \partial_0 (x_i^t - x_{best}) \tag{22}$$

In the above formula, x_{best} represents the current optimal solution. Random number generation method of Levy flight is as follows:

$$L(\lambda) = \frac{\phi \times \mu}{|v|^{\frac{1}{\beta}}} \tag{23}$$

In the above formula, μ represents normal distribution parameter, v represents Levy flight parameter, ϕ represents the number of search paths, β represents a constant, and ϕ can be calculated as follows:

$$\phi = \left\{ \frac{\Gamma(1+\beta) \times \sin\left(\frac{\pi \times \beta}{2}\right)}{\Gamma[(1+\beta) \times \beta \times 2^{\frac{\beta-1}{2}}]} \right\}^{\frac{1}{\beta}} \tag{24}$$

The location update process for the cuckoo Levy's flight is shown below:

$$x_i^{(t+1)} = x_i^t + \partial_0 \frac{\phi \times \mu}{|v|^{\frac{1}{\beta}}} (x_i^t - x_{best}) \tag{25}$$

Assuming that the probability of the appearance of a new cuckoo individual is P_a, compare the value of random number ε and P_a to judge whether a new cuckoo individual is generated. The formula for cuckoo individual generation is as follows:

$$\chi_i^{(t+1)} = \chi_i^{(t)} + \gamma \times H(P_a - \varepsilon) \otimes [\chi_j^{(t)} - \chi_k^{(t)}] \tag{26}$$

In the above formula, γ represents the judgment threshold, $\chi_i^{(t)}, \chi_j^{(t)}, \chi_k^{(t)}$ represents different cuckoo individuals, and $H(P_a - \varepsilon)$ represents the judgment function generated by cuckoo individuals.

In order to effectively solve the multi-objective optimization scheduling problem of solar photovoltaic and fuel cell combined power generation system, a new multi-objective cuckoo search algorithm is designed. In this process, an improved fitness calculation method based on Pareto dominance relation is used in this paper. The fitness function is described as follows:

$$\mathit{fitness}(x_i) = \frac{1}{s_i} \tag{27}$$

In the process of multi-objective optimization, the distribution of solutions in the target space is often crowded, and the uniformity and diversity of solutions can not be guaranteed. To solve this problem, this paper adopts a method based on niche technology to improve it, and the improved fitness function is as follows:

$$\mathit{fitness}(x_i) = \frac{1}{s_i} + I(s_i) \times n_c \tag{28}$$

Where, $I(s_i)$ is the enhancement of function fitness only for the solution with the number of dominant layers 1, and n_c represents the number of niches in solution x_i. The number of niches of n_c is calculated as follows:

$$n_c = \sum_{j=1}^{n} s(d_{ij}) \tag{29}$$

Where, d_{ij} is the Euclidean distance between the i-th solution and the j-th solution, and $s(d_{ij})$ represents the shared function, whose calculation formula is as follows:

$$s(d_{ij}) = \begin{cases} 1 - \frac{d}{\sigma}, & d \leq \sigma \\ 0, & d > \sigma \end{cases} \tag{30}$$

In the above formula, σ represents niche radius.

The archived solution is preprocessed as follows:

(1) Remove the repeated solutions in the scheduling scheme of the solar photovoltaic and fuel cell combined power generation system to avoid causing redundancy;

(2) Find out the dominant relationship of solutions in the scheduling scheme of solar photovoltaic and fuel cell combined power generation system, remove the dominated solutions and retain the non-dominated solutions.

Step by step niche reduction method is shown in Figure 4:

The steps of solving the optimization scheduling model of solar photovoltaic fuel cell combined power generation system based on multi-objective cuckoo algorithm are as follows:

(1) Initialization of the algorithm. Assumes that the solar photovoltaic power generation system of fuel cell scheduling model of the dimensions of the solution in m, said a bird's nest quantity expressed in n, the probability of new cuckoo "appear in P_a, said the cuckoo search area of the maximum and the minimum u_b and l_b respectively, said file maximum capacity in $A_{\max}$, niche radius threshold with σ, said the initial iterations in $t = 0$, said the maximum number of iterations is N, and the nest moment is $X0^t$.

(2) When $t \leq N$, proceed to the next step; otherwise, output A directly;

(3) Update the nest position, and obtain a new nest position from $X0^t$, denoted as $X1^t$;

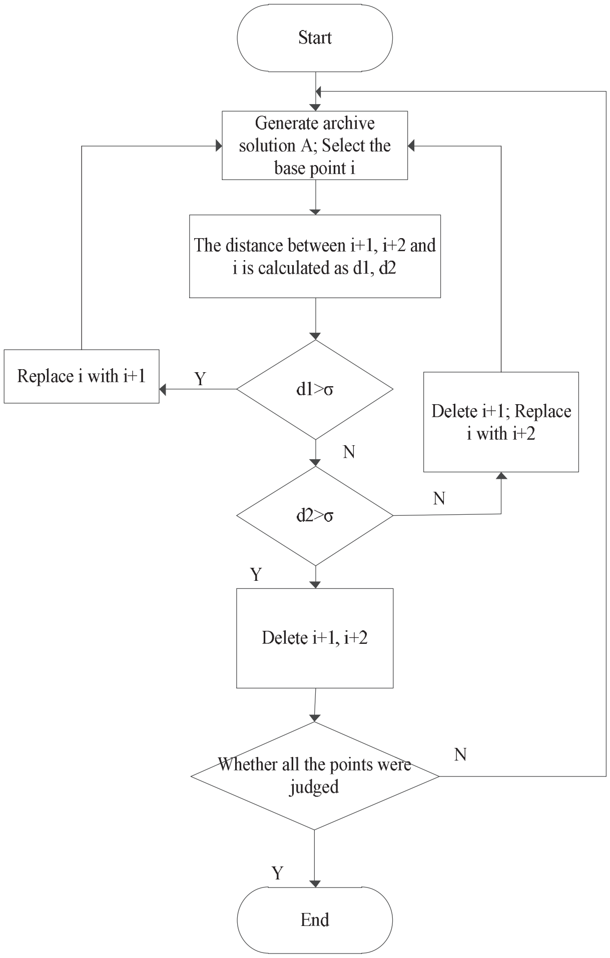

Figure 4 Implementation steps of niche progressive file reduction method.

(4) A $m \times 2n$ matrix X' is obtained by using $X1^t$. The cuckoo is rearranged according to the fitness of X', and the first n columns are selected to form moment $X2^t$.

(5) Update the solution of the scheduling model to obtain a new nest location $X3^t$.

(6) The $m \times 2n$ matrix X'' is obtained by combining $X2^t$ and $X3^t$. The cuckoo is rearranged according to the fitness of X'', and the first n columns are selected to form the matrix $X4^t$.

Table 1 Parameter description

Parameter	Describe
Power	180W
Voltage	36.2V
Current	4.97A
The open circuit voltage	44.2V
Open current	5.36V
Photovoltaic panel efficiency	14.16%
Maximum power temperature coefficient	−0.37%/K
Open circuit voltage temperature coefficient	−0.34%/K
Temperature coefficient of short-circuit current	0.09%/K
Rated battery operating temperature	48°C+/2°C
temperature	−40°C∼85°C

(7) Merge $X4^t$ into the solution set, generate a new matrix $A = [A, X4^t]$, process the solution in A, delete the repeated solution, delete the dominant solution and retain the non-dominant solution;
(8) If the formula $A > A_{\max}$ is true, step (9) is carried out; otherwise, step (10) is carried out;
(9) Use the niche reduction method mentioned above to reduce plan A. When the formula $A < A_{\max}$ is established, proceed to the next step;
(10) Let $X0^t = X4^t$, then $t = t + 1$ proceed to step (2).
(11) By such iteration, the optimal solution of the scheduling model of the solar photovoltaic fuel cell combined power generation system is obtained.

3 Experimental Design and Result Analysis

In order to verify the effectiveness of the optimization scheduling method of solar photovoltaic and fuel cell combined power generation system designed in this paper, relevant experimental tests were carried out. The solar photovoltaic panel model selected in the experiment is SGM-180D, and its parameter description is shown in Table 1.

The 6FM-12V150ah maintension-free battery, open cathode fuel cell, 12V15A controller, and 12V300W inverter were used as important experimental equipment. The battery and fuel cell parameters are shown in Tables 2 and 3.

Based on the above settings, the statistics of the data used in this experiment are shown in Table 4 below.

Table 2 Battery parameters

Parameter	Describe
Rated voltage	Open circuit voltage 12V
Nominal capacity	The rate of 10 hours is 150Ah
All charging pressure	14.4V
Float charging voltage	13.5V
Maximum charging current	0.25A

Table 3 Fuel cell parameters

Parameter	Describe
Rated voltage	24V
Rated power	200W
Conversion efficiency	≥50%
Rated current	8.3A
DC voltage range	20~40V
Purity of hydrogen used	≥99.99%
Theoretical hydrogen consumption	2.2L/min

Table 4 Data types and descriptions

Data Type	Data Volume
Photovoltaic operation data	3.58G
Battery operation data	4.27G
Electrolyzer operation data	3.56G
Fuel cell operation data	2.17G
Other equipment operation data	5.84G
Investment cost data	4.12G
Equipment update cost data	4.63G
Operation and maintenance cost data	6.31G

Combined with the above experimental Settings, the method in this paper, the reference [4] method and the reference [5] method are used to generate the optimization scheduling scheme of the solar photovoltaic fuel cell combined power generation system, and the investment costs of different schemes are compared. The results are shown in Table 5.

By analyzing the data in Table 5, it can be seen that for the photovoltaic cost, the method in this paper reduces 56.79% and 53.11% compared with the experimental comparison method; For the battery cost, the method in this paper reduces 36.87%and 49.57% compared with the experimental comparison method; For the cost of electrolytic cell, the method in this paper has reduced 30% and 58.29% compared with the experimental comparison

Table 5 Investment cost comparison of different methods

Project	Method in This Paper	Reference [4] Method	Reference [5] Method
Photovoltaic cost/yuan	37000	85630	78906
Battery cost/yuan	118000	187200	234000
Electrolyzer cost/yuan	4050	5790	9710
Fuel cell cost/yuan	6642.9	10751.3	18935.6
Total cost/yuan	165692.9	289371.3	341551.6

Table 6 Total cost comparison of different methods

Project	Method in This Paper	Reference [4] Method	Reference [5] Method
Initial equipment investment/yuan	165692.9	289371.3	341551.6
Equipment renewal cost/yuan	103652.4	247841.6	298547.1
Operation and maintenance cost/yuan	15635.8	48963.7	59874.2
Total cost/yuan	284981.1	586176.6	699972.9

method; For the fuel cell cost, the method in this paper reduces 38.21% and 64.92% compared with the experimental comparison method; For the total investment cost, the method in this paper has reduced 42.74% and 51.49% compared with the experimental comparison method, which shows that the investment cost of multiple solar photovoltaic fuel cell combined power generation systems has decreased after applying the optimization scheduling scheme of multiple solar photovoltaic fuel cell combined power generation systems designed in this paper, which shows that the scheduling method in this paper has very high economy. It can reduce the cost of multiple solar photovoltaic fuel cell combined power generation systems and lay a solid foundation for the application of multiple solar photovoltaic fuel cell combined power generation systems.

The method in this paper, the experimental comparison method are used to generate the optimal dispatching scheme of the solar photovoltaic fuel cell combined power generation system. The total costs of different schemes are compared. The results are shown in Table 6.

By analyzing the results in Table 6, it can be seen that the initial equipment investment of this method is the lowest among the three methods, and the equipment renewal cost of this method is reduced by 58.18% and 62.29% compared with the experimental comparison method; For the operation and maintenance cost, compared with reference [4] method and reference [5] method, method in this paper has reduced 68.01% and 73.89%; For the total

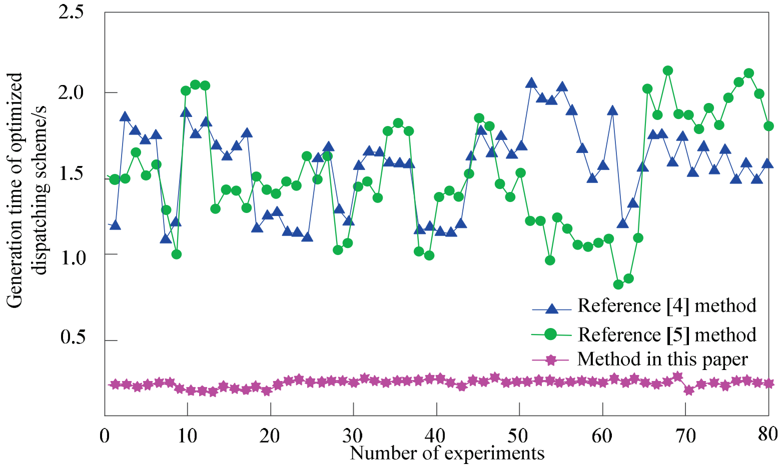

Figure 5 Generation time of optimized dispatching scheme.

cost, compared with the experimental comparison method, the method in this paper reduces 51.38% and 59.29%. The above data shows that the cost of method in this paper is lower than that of the experimental comparison method, indicating that the optimal dispatching effect of the solar photovoltaic fuel cell combined power generation system based on this method is better.

On the basis of the above, the time for generating the optimization scheduling scheme of the solar photovoltaic fuel cell combined power generation system by the method of this paper, the reference [4] method and the reference [5] method is tested. The comparison results are shown in Figure 5.

According to the data in Figure 5, the generation time of the optimization scheduling scheme of the solar photovoltaic fuel cell combined power generation system in this method is between 0.19 s and 0.25 s, the generation time of the optimization scheduling scheme of the solar photovoltaic fuel cell combined power generation system in reference [4] method is between 1.12 s and 2.16 s, and the generation time of the optimization scheduling scheme of the solar photovoltaic fuel cell combined power generation system in reference [5] method is between 0.79 s and 2.23 s. Compared with reference [4] method and reference [5] method, the generation time of the optimization scheduling scheme of this method is shorter and the overall efficiency is higher, which can be widely used in the field of optimization scheduling of solar photovoltaic fuel cell combined power generation system.

4 Conclusion

With the gradual exhaustion of traditional non-renewable energy, related fields are studying the use of new energy to replace traditional energy, and photovoltaic energy is one of them. Analysis of traditional solar photovoltaic power generation system structure, the adopted by the battery energy density is low and will not be able to realize the characteristics of the long-term storage, so lead to solar photovoltaic power generation system is difficult to expand application range, and fuel cells with high energy density, easy to long-term storage, without leakage, and other advantages, so its application to solar photovoltaic power generation systems reliability, so the solar photovoltaic fuel cell combined power generation system came into being. However, in the optimization scheduling process of traditional solar photovoltaic and fuel cell combined power generation system, the investment cost and total cost are high, and the generation time of optimization scheduling scheme is short. Therefore, a new optimization scheduling method of solar photovoltaic and fuel cell combined power generation system is designed in this paper. Through experimental tests, it is proved that the total investment cost of this method is reduced by 123678.4 yuan and 175858.7 yuan compared with the experimental comparison method, and the total cost of this method is reduced by 301195.5 yuan and 414991.8 yuan compared with the experimental comparison method. Moreover, the generation time of the optimization scheduling scheme of the solar photovoltaic and fuel cell combined power generation system is between 0.19s and 0.25s, the investment cost and total cost are low, and the optimization scheduling efficiency is high, which can further improve the performance of the solar photovoltaic and fuel cell combined power generation system.

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