RESEARCH ON FUEL CELL ENERGY STORAGE CONTROL AND POWER GENERATION SYSTEM

Jing Pan

Taiyuan University， Shanxi, 467036, China

*Corresponding author; E-mail: pandaj@foxmail.com

In order to realize the continuous stability of photovoltaic power generation system and the controllability of thermal energy storage, a photovoltaic fuel cell combined power generation system consisting of photovoltaic cell array, proton exchange membrane fuel cell, alkaline electrolysis cell and super capacitor is proposed. The system, at the same time, establishes the mathematical model of its various components and the system cost model, designs the thermal energy distribution of the thermal energy storage management coordination system, and uses the high-efficiency battery to meet the load requirements of the power system. In addition, the paper uses simulation technology as a research method to build a simulation model of hybrid fuel cell thermal energy storage control and power generation system, and analyzes the system's thermal energy supply and demand balance. The simulation results confirm that the photovoltaic fuel cell hybrid power generation system has high economic performance, can meet the user's power and thermal energy requirements, and realizes the requirement of completely independent power supply.

Key words*: Thermal energy storage control; photovoltaic fuel cell; power generation system; optimal scheduling; electric heating combined supply*

1. Introduction

At present, all countries in the world use centralized transmission of power grids, which is based on large-capacity centralized power generation. However, the fact that large-scale power outages occurred in the large power grids of the United States, Canada, and Taiwan in recent years indicates that while the "large units, high voltage, and large power grids" are developing modes, attention should be paid to the development of green and environmentally dispersed power sources. It will be the 21st century [1]. The development direction of the power industry. The decentralized power supply has a short construction period, covers an extremely small area, and is installed near the load, saving the construction and transmission network transmission costs and reducing line losses. The main devices that can serve as distributed power generation tasks include internal combustion engines, gas turbines, fuel cells, solar cells, and wind turbines [2]. The variety of fuels and the diversity of new technologies in thermal energy have led to many new features in the development of the thermal sciences, such as comprehensive and multidisciplinary intersections. Actively develop distributed power generation technologies such as fuel cells and photovoltaic power generation, reduce the negative impact of the "thermal energy crisis" on society, reduce environmental pollution caused by fossil fuels, and establish a sustainable thermal energy structure to build China's future thermal energy security system.

Solar energy is a kind of renewable heat that is ubiquitous, rich in resources and free from any environmental pollution. China has abundant solar energy resources, and the area with total annual solar radiation of more than 1050 kWh/m2 accounts for more than 96% of the country's land area, as shown in Figure 1. The use of residential solar distributed power generation technology can not only effectively alleviate the pressure of urban power supply shortage, solve the power supply problem in remote areas, but also reduce pollutant emissions and improve environmental quality [3].

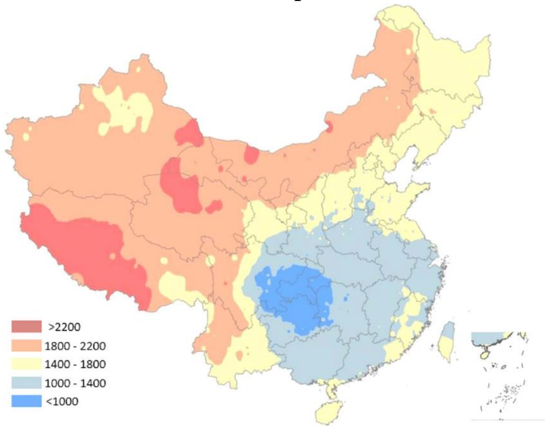

Fig.1 Distribution of solar energy resources in China

In this paper, a photovoltaic/fuel cell combined power generation system using a battery and a hydrogen energy system is proposed, and a control scheme with a double-layer control structure of an electrothermal control layer and an electrothermal scheduling layer is proposed. The electrothermal control layer directly controls the power generation process of the hybrid system, controls and coordinates the electric energy, thermal energy and reaction gas of the hybrid system. The electric heating scheduling layer indirectly controls the power generation process of the hybrid system through the electric heating control layer, rationally dispatches the power generation process of the hybrid power generation system, and optimizes the hybrid power generation system. performance. On the basis of the mathematical model and cost model of each component of the system, the simulation platform of the combined power generation system is constructed, and the thermal energy management strategy is designed to coordinate the thermal energy distribution of the joint system, and the system cost and the balance of supply and demand of thermal energy throughout the year are analyzed.

2. Photovoltaic fuel cell performance prediction model establishment

2.1. Photovoltaic fuel cell model

Components of photovoltaic/fuel cell cogeneration systems include photovoltaic modules, fuel cells, electrolysis cells, hydrogen compressors, hydrogen tanks, batteries, and other ancillary equipment. Figure 2 shows the topology of the system. The input and output characteristics of a photovoltaic cell can be determined by its volt-ampere characteristics.

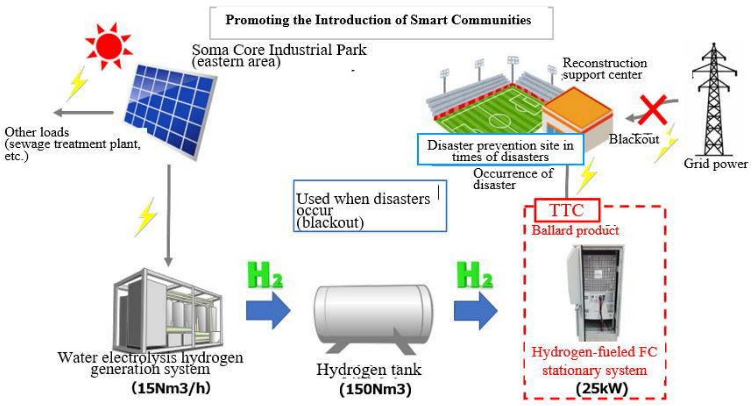

Fig.2 Photovoltaic fuel cell cogeneration system

Photovoltaic cells are the basic unit for converting solar energy into electrical energy. A plurality of batteries is connected in parallel and packaged to form a photovoltaic module. The model of the photovoltaic cell can be represented by an equivalent circuit as shown in Figure 3 [4].

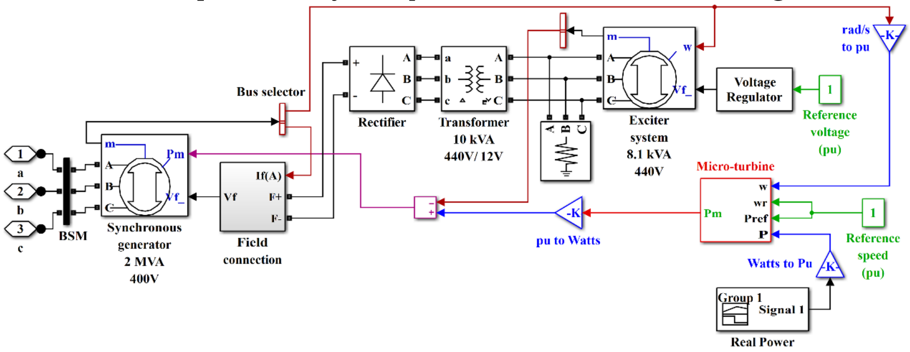

Fig.3 Equivalent circuit of photovoltaic cell

The volt-ampere characteristic of a photovoltaic cell is the relationship between its output voltage and output current at a certain illumination intensity and temperature. According to the literature [5], for a given photovoltaic intensity and temperature of a photovoltaic cell, its output voltage and current can be obtained by using the photovoltaic cell volt-ampere characteristic model under standard conditions, using light intensity and temperature parameters to correct. The relationship between the output voltage A and the B current of a photovoltaic cell under standard conditions (light intensity 1 kW/m2, operating temperature 25 °C) can be expressed as:

$$I_{STC} = I_{SC}\left\{1-K_1\left[\exp\left(K_2 V_{STC}^m - 1\right)\right]\right\} \tag{1}$$

Among them, coefficient $K_1=0.01175$, coefficient $K_4=\ln\left[1/(K_1+1)\right]$, coefficient $K_2=K_4/V_{OC}^m$, coefficient $K_3=ln\left[I_{sc}(1+K_1)/\left(K_1 I_{sc}-I_{mpp}\right)/K_1 I_{sc}\right]$, $m=ln\left[(K_3/K_4)/\ln\left(V_{mpp}/V_{oc}\right)\right]$. I_{STC} represents the battery current under standard conditions, I_{SC} represents the short-circuit current of the battery, I_{mpp} represents the battery current at the maximum power, V_{STC} represents the battery voltage under standard conditions, V_{oc} represents the open circuit voltage of the battery, and V_{mpp} represents the battery voltage at the maximum power. For any given light intensity and temperature, the output voltage V_{cell} and current I_{cell} of a photovoltaic cell can be expressed as:

$$I_{cell} = I_{STC} + \alpha_{SCT}\frac{G}{G_{STC}}\Delta T_C + \left(\frac{G}{G_{STC}} - 1\right) I_{scSTC} \tag{2}$$

$$V_{cell} = V_{STC} + \beta_{OCT}\Delta T_C - R_s\left(I - I_{STC}\right) \tag{3}$$

Of which: $\Delta T_c = T_a + \frac{G}{800}\left(NPCT - T_{a,ref}\right)$ · α_{SCT} represents the battery short-circuit current temperature coefficient (Amps/°C), β_{OCT} represents the battery open circuit voltage temperature coefficient, NOCT represents the standard test temperature, ΔT_C represents the compensation temperature, T_a represents the battery given temperature, $T_{a,ref}$ represents the standard temperature, and R_s represents the equivalent series connection of the module. Resistance, G represents the given light intensity, and G_{STC} represents the light intensity of the standard test. According to the illumination, ambient temperature and load, the volt-ampere characteristic model of the photovoltaic cell can be used to determine the output power of the photovoltaic cell, and the maximum power output of the photovoltaic cell can also be calculated, thus providing a basis for system design and simulation.

2.2. Photovoltaic module characteristics model

The characteristic curve of the photovoltaic module is shown in Figure 4. The output power of a photovoltaic cell increases as the amount of solar radiation increases, and decreases as the temperature increases. Under a certain temperature and radiation quantity, the system has a maximum power point, and the solar energy can be fully utilized by a maximum power point tracker [6].

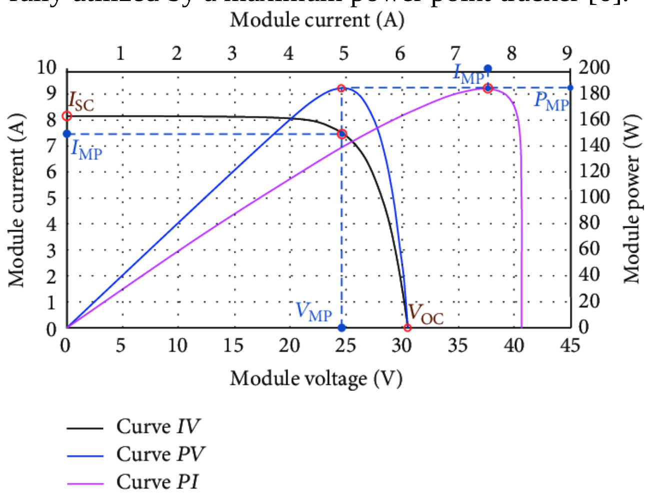

Fig. 4 Characteristic curve of PV modules

For the convenience and accuracy of research and simulation, mathematical models are needed to describe the input and output characteristics of photovoltaic modules. According to the variation characteristics and the reasons for the changes shown by the voltage-current density curve, a mathematical formula is proposed to fit the polarization curve of the photovoltaic module. The voltage-current density curve shows changes in characteristics caused by four factors: activation loss, fuel penetration and internal short-circuit current, ohmic loss, and mass transfer loss.

2.2.1 Activation loss

The loss of activation is mainly due to the slow reaction rate occurring at the electrode surface. When a chemical reaction that drives electrons away or enters the electrode, part of the voltage generated is consumed. In any form of electrochemical reaction, the voltage drop across the electrode surface always follows a similar curve and can be described by the Tafel formula. The voltage drop for the activation loss of a photovoltaic fuel cell can be expressed by the following Tafel formula:

$$\Delta V_{act} = A\ln\left(i / i_0\right) \tag{4}$$

Where: ΔV_{act} represents the activation loss voltage drop, and A and i_0 are two constants depending on the electrode and battery operating conditions. For slow electrochemical reactions, the constant A will be higher. If the electrode reaction speed is increased, the constant i_0 will also increase. This formula is only valid in the case of $i_0 > i$.

2.2.2 Fuel penetration and internal short circuit current

Fuel penetration and internal short circuit currents also create a loss of voltage drop across the photovoltaic module. In a practical photovoltaic module, hydrogen diffuses from the anode through the electrolyte to the cathode. Here, due to the action of the catalyst, hydrogen reacts directly with oxygen and cannot generate current on the external circuit of the battery. The phenomenon of hydrogen waste caused by a small amount of fuel of the electrolyte is called fuel penetration. Despite the ionic conductivity of the proton exchange membrane of a photovoltaic module, it is used as an electrolyte, but there is always a small amount of electron conduction in the electrochemical reaction, which also forms an internal short circuit current of the photovoltaic module. To represent the voltage, drop of the PV module resulting from this loss, Equation (4) can be rewritten as:

$$\Delta V_{act} = A\ln\left(\left(i+i_n\right)/i_0\right) \tag{5}$$

Where: i_n represents the internal short-circuit current density of the PV module. Internal short-circuit current and fuel penetration have little effect on battery efficiency. However, in the case of low temperature fuel cell photovoltaic modules, its effect on the open circuit voltage is significant.

2.2.3 Ohmic loss

The ohmic loss is the resistance of the electrode and the voltage loss caused by the resistance encountered when the ions flow in the electrolyte. This voltage loss is always proportional to the current density and is therefore referred to as ohmic losses. It can be expressed as:

$$\Delta V_{ohm} = ir \tag{6}$$

Where: r represents the resistance per unit area, and i represents the current density.

2.2.4 Mass loss

Mass transfer loss is caused by changes in the concentration of reactants on the electrode surface when used by photovoltaic modules. Because the working photovoltaic module emits current that consumes oxygen and hydrogen, the concentration of reactants on the surface of the electrode is reduced, that is, the pressure of oxygen and hydrogen is reduced. P_1 decrease in the pressure of the reaction gas will cause a drop-in voltage. If the hydrogen pressure changes from A to P_2, the voltage change is:

$$\Delta V=\frac{RT}{2F}\ln\left(\frac{P_2}{P_1}\right) \tag{7}$$

In order to express the change in air pressure as a change in current, a limit current density i_1 is first assumed, at which the fuel is sufficiently consumed at the maximum supply speed. The current density cannot exceed this value because we cannot provide fuel gas at a greater rate. At this limit current density value, the gas pressure value just reaches zero. If the gas pressure is P_1, the battery current density is zero, and assuming that the current linearly drops to zero when the current density is reached, then the gas pressure at the current density i is given by: $P_2 = P_1\left(1-\frac{i}{i_1}\right)$. The voltage drop resulting from the change in the pressure of the reaction gas can be expressed as:

$$\Delta V=\frac{RT}{2F}\ln\left(1-\frac{i}{i_1}\right) \tag{8}$$

2.3. Hydrogen storage system

In a hybrid power generation system, hydrogen produced in an alkaline electrolytic cell is placed in a high-pressure vessel for use by a fuel cell for power generation. The derivative of the hydrogen pressure p_{HS} in the high pressure vessel and the flow rate of the hydrogen produced by the cell q_{AE} are proportional to the difference between the flow rate q_{PEMFC} of the hydrogen consumed by the fuel cell, expressed as:

$$\frac{dp_{HS}}{dt}=\frac{RT}{V}\left(q_{AE}-q_{PEMFC}\right) \tag{9}$$

Where: V represents the volume of the hydrogen storage container, and T represents the hydrogen temperature in the hydrogen storage container.

2.4. Capacitance Model

The supercapacitor plays a short-term energy storage role in the power generation system. It supplies power to the system during discharge and stores the surplus power of the system during charging. In this study, supercapacitors were connected to the system via a bidirectional DC-DC converter. When the bidirectional DC-DC converter operates in different ways, it's working efficiency is different. It is assumed here that the efficiency of the bidirectional DC-DC converter is the same when operating in different modes. If the capacitance of the supercapacitor is C, then the supercapacitor power can be obtained as:

$$P_{UC} = kCV_{UC}\frac{dV_{UC}}{dt} \tag{10}$$

Where: the parameter k is defined as:

$$k=\begin{cases}\eta & discharge\\ \eta^{-1} & charge\end{cases} \tag{11}$$

The energy stored in the supercapacitor is proportional to the square of the terminal voltage of the supercapacitor. When the capacitor voltage drops from the rated voltage to 70%, the supercapacitor releases 51% of the total energy. If $V_{\sup}$ is the rated maximum operating voltage of the supercapacitor and the operating range of the supercapacitor is set to $0.7V_{\sup}$: $V_{\sup}$, then the maximum energy that the supercapacitor can store is:

$$E_{UC} = C\left(V_{\sup}^2 - 0.49V_{\sup}^2\right) \tag{12}$$

3. Thermal energy storage strategy and control model

3.1. Electrochemical model thermal energy model

For an independent photovoltaic thermal system, some of the solar energy during the day must be stored to meet the load requirements of insufficient or no light. Usually solar energy is enough in spring, summer and autumn, while solar energy is less in winter, so part of the heat in spring, summer and autumn must also be stored to compensate for the lack of sunshine in winter. The purpose of the thermal management strategy is to coordinate the various components of the combined power generation system to achieve a balance of thermal energy supply and demand throughout the year while meeting the daily needs of the user load.

The battery has a short service life and is expensive, so the battery is not suitable for long-term storage of a large amount of heat. Due to its high thermal energy storage efficiency, the battery can be used to meet the short-term daily demand of the load; the long life and low-price hydrogen tank can be used for a long time. Store a lot of heat. This can protect the seasonality of light while improving solar energy utilization. Fuel cells are only used in emergency situations where the thermal energy storage of photovoltaic cells and batteries is insufficient to meet load requirements, which reduces the storage capacity of hydrogen and extends the life of the fuel cell, thereby reducing the initial cost and maintenance cost of the system.

The output voltage of a single cell consists of four parts: open circuit voltage E_{nernst}, active polarization η_{act}, ohmic polarization η_{ohm}, and concentration polarization η_{con}:

$$V_{cell} = E_{nernst} + \eta_{act} + \eta_{ohm} + \eta_{con} \tag{13}$$

The open circuit voltage E_{nernst}, also known as the thermodynamic equilibrium potential, also known as the Nernst potential, is the open circuit voltage of the photovoltaic fuel cell when there is no current flowing and the internal is in equilibrium. Currently, the photovoltaic fuel cell is in an inoperative state. The dominant role in the small current range is the activation polarization η_{act}, which is the force that drives the electrochemical reaction. When the current is further increased, the ohmic polarization η_{ohm} will dominate, which is the main voltage loss of the fuel cell during normal operation. The thermodynamic equilibrium potential E_{nernst} is the potential when no current flows through the photovoltaic fuel cell and the entire electrochemical system is in equilibrium.

$$E_{nernst} = -\frac{\Delta G_0}{2F} + \frac{RT}{2F}\ln\left(\frac{\alpha H_2 \alpha O_2^{0.5}}{\alpha H_2 O}\right) \tag{14}$$

This formula represents the relationship between the reversible electromotive force of the battery at a certain temperature and the activity of each component participating in the reaction. Where a represents the activity of each reactive species, ie the proportional relationship between the partial pressure of the material and the standard pressure.

3.2. Gas change heat model

Photovoltaic fuel cell temperature is an important working parameter of photovoltaic fuel cells and is one of the key factors affecting power generation quality [7]. When the temperature rises, the output voltage of the photovoltaic fuel cell increases, and the working efficiency increases. Excessive temperature of the photovoltaic fuel cell will cause dehydration of the proton exchange membrane, increase in the resistance of the proton exchange membrane, increase in calorific value, deterioration of the performance of the photovoltaic fuel cell, and may even cause damage to the proton exchange membrane. When the temperature of the photovoltaic fuel cell is too low, the electrochemical reaction speed of hydrogen and oxygen is lowered, and the diffusion ability of the reaction product water in the proton exchange membrane is lowered, which easily causes the cathode flooding problem to occur. Generally, the temperature of a photovoltaic fuel cell cannot exceed 100. Practical studies have shown that the optimal operating temperature range of a photovoltaic fuel cell is 70-90 °C. Therefore, establishing a thermal model of a photovoltaic fuel cell is important for maintaining the temperature of the photovoltaic fuel cell in an optimal temperature range, reducing the temperature fluctuation of the photovoltaic fuel cell, and improving the performance of the photovoltaic fuel cell.

When a photovoltaic fuel cell generates electricity, part of the energy released by hydrogen is converted into heat energy that is absorbed by the photovoltaic fuel cell. According to the law of conservation of energy, the absorption rate of thermal energy of a photovoltaic fuel cell can be expressed as:

$$q_{stack} = P_{tot} - P_{elec} - q_{loss} - q_{cool} \tag{15}$$

Where: q_{stack} represents the thermal energy flow rate of the photovoltaic fuel cell, P_{tot} represents the total energy flow rate of the electrochemical reaction of the photovoltaic fuel cell, P_{elec} represents the external output power of the photovoltaic fuel cell, and q_{loss} represents the thermal energy flow rate of the photovoltaic fuel cell to the outside.

$$C_t \frac{dT}{dt} = q_{stack} \tag{16}$$

Where: C_t represents the heat capacity of the photovoltaic fuel cell, T represents the temperature of the photovoltaic fuel cell, and q_{stack} represents the thermal energy flow rate of the photovoltaic fuel cell.

The heat energy flow rate absorbed by the heat exchanger can be calculated by the following formula [8].

$$q_{cool} = C_{cw}\left(T_{cw}^{0} - T_{cw}^{in}\right) = UA_{HX} LMTD \tag{17}$$

Where: q_{cool} represents the cooling system absorbs thermal energy flow rate, T represents the temperature of the photovoltaic fuel cell, C_{cw} represents the cooling water heat capacity, T_{cw}^{0} represents the heat exchanger outlet cooling water temperature, T_{cw}^{in} represents the heat exchanger inlet cooling water temperature, and UA_{HX} represents heat exchange Capacity, $LMTD$ represents the logarithmic mean temperature difference of the heat exchanger cooling water inlet and outlet, h_{cond} represents the heat transfer parameter of the heat exchanger, and h_{conv} represents the heat radiation parameter of the heat exchanger. According to formula (15), the temperature of the cooling water at the outlet of the heat exchanger can be calculated by the formula (18):

$$T_{cw}^{0} = T_{cw}^{in} + \left(T - T_{cw}^{in}\right)\left[1 - \exp\left(-UA_{HX} / C_{cw}\right)\right] \tag{18}$$

4. Simulation study

Figure 5 shows the thermal energy storage level of the battery throughout the year. As can be seen from the figure, in the spring, summer and autumn, the battery can basically meet the daily load requirements of the user. However, in the winter, the energy stored by the battery alone cannot meet the load requirement of insufficient or no light period. At this time, the fuel cell needs to be activated to supplement the insufficient portion; the heat generated by the fuel cell can heat the household in the winter, so that Further improve the utilization of solar energy and save the heating costs of households.

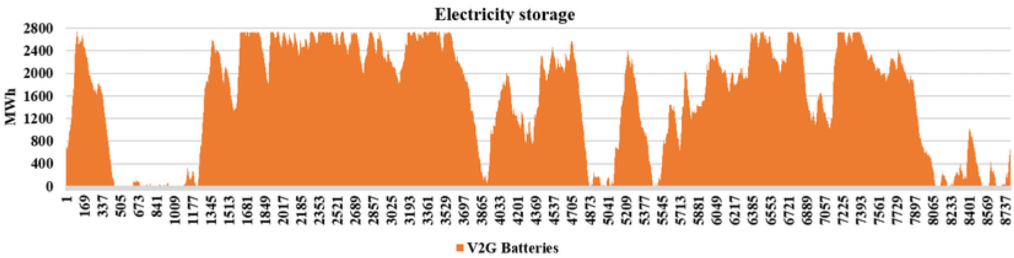

Fig.5 Storage level of the battery throughout the year

In the 0~24-hour interval, Figure 6(a) shows that the PV array has a long working time and more output energy. Figure 6(b) shows that the instruction given by the optimal scheduling algorithm also increases the working time of the alkaline electrolyze. And the power PAE (k) is increased; in the interval of 120~144 hours, Figure 6(a) can see that the PV array has short working time and less output power, and Figure 6(b) shows the instruction given by the optimal scheduling algorithm at this time. It also reduces the operating time of the alkaline electrolytic cell and reduces the power PAE (k). This shows that the optimal scheduling electric heating management system can set the working power of equipment such as alkaline electrolyzes of the hybrid power generation system according to the daily PV array and the user's electric heating demand.

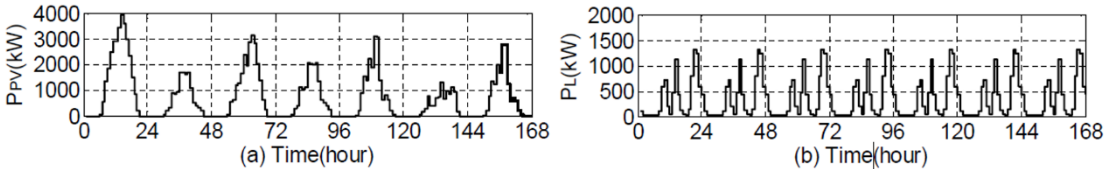

Fig. 6 Curve of PV array output power and thermal energy demand

The state standard variance based on the optimal scheduling algorithm is smaller than the state standard variance of the system based on the priority scheduling algorithm, which indicates that the performance of the system based on the optimized scheduling algorithm is more stable and reliable. By comparing the $MH_2(k)$ curves of the hydrogen species in the hydrogen storage tanks of the two systems, it can be found that their trends and values are very close. Comparing the thermal energy Ehw(k) curves of the two systems of hot water storage tanks, it is found that the system based on the optimized scheduling algorithm has a large Ehw(k) value. Moreover, in the interval of 120~168 hours, the Ehw(k) curve of the system based on the priority scheduling algorithm decreases rapidly, and the Ehw(k) curve of the system based on the optimal scheduling algorithm maintains a relatively high value, which means A system that optimizes the scheduling algorithm can save more heat. By comparing the $MH_2(k)$ and Ehw(k) curves of the two systems, the two systems store nearly the same amount of hydrogen energy, and the system based on the optimized scheduling algorithm stores more heat energy. The system that optimizes the scheduling algorithm is superior to the system based on the priority scheduling algorithm.As shown in Figure 7.

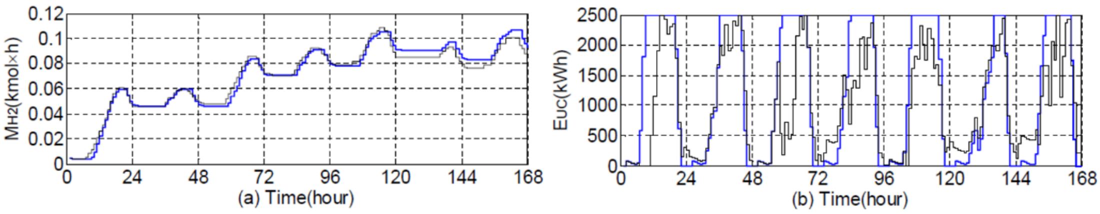

Fig. 7 Curve of hydrogen storage capacity of mixed system and heat storage of mixed system

5. Conclusion

This paper proposes to use the photovoltaic/fuel cell combined power generation system to meet the user's annual load demand. Based on the built-in component mathematical model and system cost model, the simulation platform of the joint system is constructed, and the energy distribution of the energy management strategy coordination joint system is designed. After the paper goes from steady state to dynamic, from equipment to system, from design to control, from simple to complex and gradual research process, this thesis is the first to use the simulation method to realize the photovoltaic fuel cell hybrid power generation system in detail and completely. The design and control problems in the application process of hybrid power generation system form a relatively complete application system of hybrid fuel cell power generation technology. The system configuration design, dynamic simulation, coordinated control, and electrothermal scheduling research process and the obtained method results not only provide a large basis for further research, development and application of the system, but also can be used for other new energy-fuel cell hybrid power generation. Provide a reference for the research and application of the system.

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