DESIGN AND SIMULATION OF HYBRID THERMAL ENERGY STORAGE CONTROL FOR PHOTOVOLTAIC FUEL CELL

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Abstract: *Objective: Through the design and simulation of hybrid thermal energy storage control of photovoltaic fuel cell, the hybrid thermal energy storage system of photovoltaic fuel cell is further optimized. Method: Firstly, the mathematical model of photovoltaic power generation is established. Then voltage feedback, power feedback, disturbance observation method and conductance increment method are used to track the maximum power of the system. After that, the dynamic model of proton exchange membrane fuel cell is established, and the former MPPT control strategy is used to keep the voltage stable. Finally, simulation experiments are carried out to verify the effectiveness and superiority of the proposed control strategy and battery model. Results: The hydrogen pressure on the anode side of the fuel cell can be maintained at 0.3MP at a fast speed. In the process of output, the voltage of fuel cell is much smaller than the polarization voltage of fuel cell. Its voltage decreases gradually from 14 seconds to 16 seconds. Once the illumination changes suddenly, the system can also accurately locate and track the maximum power point, and output the electric quantity. Conclusion: Based on the mathematical model of photovoltaic power generation and the dynamic model of proton exchange membrane fuel cell, the hybrid thermal energy storage system of photovoltaic fuel cell has great advantages. It can keep the voltage stable and track the maximum power of the system in time, which is of great significance for the follow-up research in photovoltaic power generation.*

Key words: *photovoltaic; fuel; thermal energy; MPPT; storage*

1. Introduction

With the rapid development of China's economy, the demand for power supply is growing [1, 2]. The traditional energy is mainly coal and oil. The excessive use of these energy sources will lead to a series of problems, such as greenhouse effect, haze weather, ecological damage, etc., which seriously affect the quality of life of the people. This makes people deeply realize that the energy composition structure must be adjusted and green renewable energy must be vigorously developed [3]. Therefore, developed countries such as Europe and the United States first proposed the distributed generation technology based on renewable energy. Common distributed generation includes photovoltaic, fuel cell, biomass power generation, wind power, etc. With clean energy and oxygen as reactants, fuel cell has the advantages of high energy conversion efficiency, high energy density, strong operability, low operating noise, low thermal radiation, low emission and pollution-free, which has attracted social attention [4, 5]. Proton exchange membrane fuel cell (PEMFC) has the advantages of rapid start-up at low temperature, modular structure, convenient maintenance, and no pollution due to the reactant being water [6]. PEMFC is recognized as the best choice of electric vehicle, surface submarine, fixed power station, communication standby power and mobile power. In small and medium power applications, PEMFC has occupied an indispensable position and has become the most potential type of fuel cell [7, 8]. The raw material of PEMFC is hydrogen. By converting hydrogen energy into electric energy, it is an indispensable part of micro grid research and plays an important role in the development of micro-grid research.

Excessive dependence on fossil energy has caused serious environmental pollution and energy crisis. The development and utilization of new energy and the improvement of energy structure are the urgent needs of all countries in the world [9]. Solar energy is a kind of renewable energy which is ubiquitous, rich in resources and free from any pollution. Photovoltaic power generation technology with photovoltaic cells as the core is an important application field of solar energy development and utilization. China is rich in solar energy resources. The area with annual total solar radiation more than 1050k Wh / 2m accounts for more than 96% of the land area [10, 11]. China's remote western region is characterized by poor environment, vast territory and sparse population. If the traditional power grid is used to meet the demand of people in these areas, it will need a very large cost. Therefore, it is a very good solution to solve this kind of no electricity shortage problem to adopt the photovoltaic hybrid power generation system which is pollution-free, not limited by the region, easy to install and flexible to configure.

In this study, a new tracking strategy and control algorithm are proposed by optimizing the hybrid thermal energy storage system of photovoltaic fuel cell, and the mathematical model of photovoltaic power generation and the dynamic model of proton exchange membrane fuel cell are established, which can improve the stability of power generation system output. The voltage of the system is feedforward controlled by the MPPT control system. By using this method, the stability, anti-interference ability and dynamic response ability of power generation system can be improved. The simulation experiment is of great significance for the optimization and application of the hybrid thermal energy system of photovoltaic fuel cell.

2. Method

2.1 Mathematical model of photovoltaic power generation

Photovoltaic power generation system is a new type of power generation system. Its main working principle is to convert the radiated solar energy into widely used power. If the solar radiation is in non-uniform semiconductors or metals, there will be an electromotive force difference in different parts, and eventually there will be circuit return. Among them, the output of photovoltaic cells has a certain relationship with the light intensity of solar energy and the temperature of the cell surface. V-I is used to represent the output characteristics of photovoltaic cells. Its photovoltaic characteristics will change with the intensity of solar radiation and the temperature of the cell surface. The relationship between them can be expressed as Eq. (1):

$$I = f(V, T, S) \tag{1}$$

In the Eq. (1), S represents the solar light intensity, and T represents the temperature of the battery surface. The equivalent circuit diagram of the output voltage of the photovoltaic cell is shown in Fig. 1:

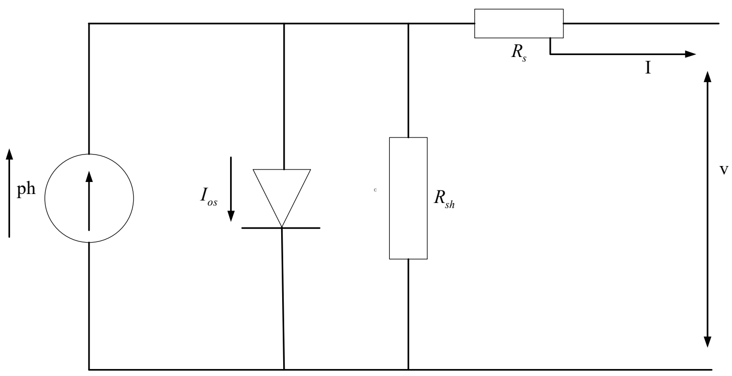


Figure 1 Equivalent circuit diagram

In the Fig. 1, Iph represents the photo generated current. When the light is stable and unchanged, its photo generated current will not be affected by other external environment, so it can be regarded as a constant power supply. When the load is connected to the photovoltaic module, the voltage at both ends of the load will have an impact on the current on the P-N junction and have a negative effect on it. The current on the P-N junction is represented by Ios. In addition, there is a certain relationship between the Rsh and the leakage current of the battery to the ground, which is inversely proportional. If the photovoltaic cell is blocked in the process of current output, resistance Rs will be generated. Among them, the purity of semiconductor materials and the depth of P-N junction will greatly determine the resistance Rs. The larger the resistance value is, the more energy is lost in the circuit, and the lower the working efficiency of photovoltaic cells.

In this study, according to the circuit characteristics and internal structure of photovoltaic cells, a mathematical model is established as Eq. (2), Eq. (3), Eq. (4), and Eq. (5):

$$I_{ph} = I_{ph(T1)}[1 + k_0(T - T_1)] \tag{2}$$

$$I_{ph(\mathrm{T1})} = S \bullet I_{SC}(T_{nom}) / S_{nom} \tag{3}$$

$$K_0 = I_{SC(T2)} - I_{SC(T1)} / (\mathrm{T}_2 - \mathrm{T}_1) \tag{4}$$

$$I_{0S} = I_{0S(nom)} \left\{ \exp[\frac{q(V + IR_s)}{AKT}] - 1 \right\} \tag{5}$$

In the above mathematical model, the representative of Iph is photocurrent, which is proportional to the light intensity. The standard light condition is S = 1000W / m^2. The short-circuit current at this temperature T1 is expressed in $I_{SC(T1)}$. The current of i0s flowing through the diode under standard light conditions is represented by $I_{SC(T2)}$. Among them, the short-circuit current of photovoltaic cell is represented by I_{SC}. Snom represents the light intensity under standard conditions. S represents the actual light intensity. The saturation current of photovoltaic cell is expressed in $I_{0S(nom)}$. The output current at the load end and the output voltage at the load end are expressed in I and V respectively. The ideal factor of P-N junction is expressed by A. In general, its value range is limited between 1 and 2. Kelvin temperature scale is expressed by T, and K0 is the number of short-circuit current temperature. Its calculation method is $A / {}^\circ\mathrm{C}$. K represents Boltzmann constant, which can be taken from 1.3810 to 23J/K.

Then, according to the parameters of Solarex MSX60 60W, the model is further established. Through calculation, K0=0.0024/ °C. Therefore, it can be further inferred that:

$$I_{ph} = S \bullet \frac{3.8}{1000} \times [1 + 0.0024(T - 25T - 273)] \tag{6}$$

$$I = I_{ph} - I_{os} \bullet \left\{ \exp[\frac{q(V + IR_s)}{AKT}] - 1 \right\} \tag{7}$$

2.2 Maximum power tracking

Photovoltaic cells have great instability in the process of output, and are easily affected by external environment, such as solar radiation intensity and panel temperature. If the output of the battery and its inverter cannot be properly matched, or the maximum power of the photovoltaic cell cannot be grasped, a lot of energy will be lost. Therefore, it is necessary to use appropriate control methods to control photovoltaic cells and control circuits.

2.2.1 Voltage feedback

As shown in the Fig. 2 and Fig. 3, it is a simple, effective and practical maximum power tracking method used in the research. By using this method, the voltage of the battery board can be effectively adjusted to be equal to the test voltage of the maximum power, so as to further achieve the purpose of tracking the maximum power point. In this process, the voltage corresponding to the maximum power point of the photovoltaic fuel cell can be tested in advance. However, once it is greatly affected by the external environment, the system cannot track the maximum power point, which will eventually lead to a large error.

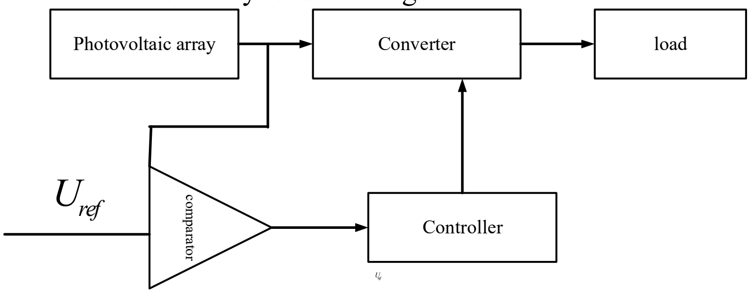


Figure 2 Fixed reference voltage method

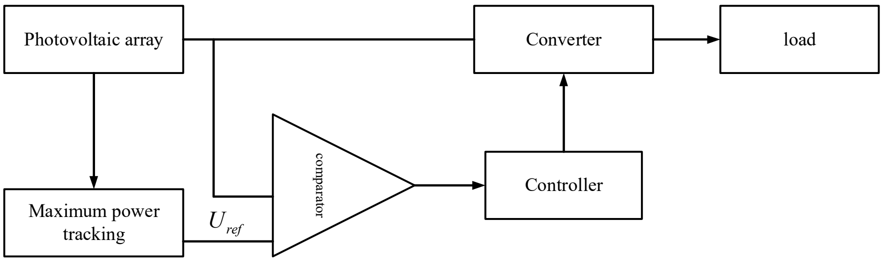


Figure 3 Variable reference voltage method

2.2.2 Power back-off

As shown in Fig. 4, another method for maximum power point tracking in this study is power back-off method. The voltage regression method has some defects. Once the environment changes, it will be unable to adapt to the situation, and ultimately cannot complete the purpose of tracking the maximum power point. Therefore, a certain logic judgment is added to the power back-off method. After joining, it will not be affected by any weather environment, and can track the maximum power point in any weather environment. Relatively speaking, although the calculation amount of this method is relatively large and complex, it has great advantages. It can effectively save the energy loss of the circuit and improve the overall effect of the system operation.

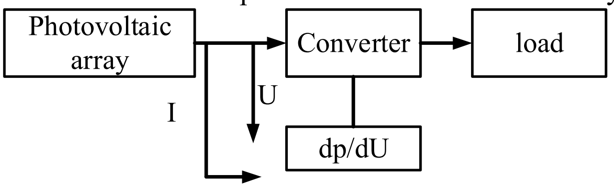


Figure 4 Power back-off method

2.2.3 Incremental conductance

Incremental conductance method is one of the most widely used methods, as shown in Fig. 5. Its main principle is to further realize the function of MPPT by comparing the relationship between the instantaneous immittance and the variation of immittance of photovoltaic array. As shown in Fig. 6, the output P-U curve and dP/dU change characteristics of photovoltaic array are shown. It can be seen from this figure that this curve has a first-order continuous differentiability. Among them, the dP/dU on both sides of the maximum power point is different and opposite. However, the dP/dU value at MPP is equal to zero. As shown in the Fig. 5 below, it can be seen that the basic principle and power back-off of this method are the same. The starting point is that dP/dU is equal to zero, which is the same as the logic judgment equation of power back-off. dP/dU = 0 can be further rewritten as Eq. (8):

$$\frac{dP}{dU} = \frac{d(UI)}{dU} = I + U\frac{dI}{dU} = 0 \qquad (8)$$

Among them, the power is represented by P, the current is represented by I, and the voltage is represented by U. After further sorting out the above equations, it can be obtained:

$$\frac{dI}{dU} = -\frac{I}{U} \qquad (9)$$

Among them, dI represents the current difference measured before and after increment, dU represents the voltage difference measured before and after increment. Therefore, in this study, it is only necessary to compare the value of dI / dU with I/U, and then the direction of next value change and size after change can be obtained. If the incremental value and electric value can meet the requirements of the above equations, the system power can reach the maximum power point.

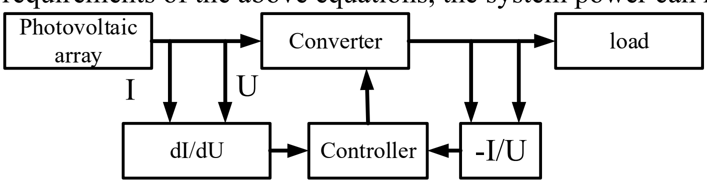


Figure 5 Conductivity increment

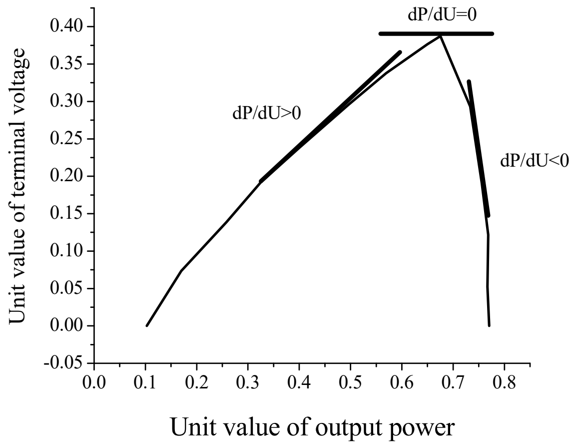


Figure 6 Output P-U curve and change characteristics of dP/dU of photovoltaic array

2.3 Dynamic model of PEMFC

In order to simplify the fuel cell model, the following assumptions are made in this study. The first point is that the temperature of the battery stack changes very slowly, so it is assumed that the temperature of the battery stack is constant. The second point is that the reactants will continue to feed the fuel cell and keep it working at a high flow rate. The third point is that water can always be generated in a liquid reactor. The water tank and water separator can effectively control the liquid water. By this method, the situation of water submergence can be avoided. The fourth point is to assume that the mole fraction of the reactant at the entrance is constant. Nitrogen and oxygen are evenly mixed at a ratio of 21:79 and then fed to the cathode.

According to the law of ideal gas, there is a certain relationship between the partial pressure of each gas and the amount of gas in the battery, which is in direct proportion. The amount of gas can be obtained by subtracting the amount of gas consumed and flowing out from the amount of gas flowing. The following Eq. (10), Eq. (11), and Eq. (12) are the conservation law of cathode Moore:

$$\frac{dp_{H2}}{dt} = \frac{RT}{V_A}(H_{2in} - H_{2used} - H_{2out}) \tag{10}$$

$$\frac{dp_{H2O_A}}{dt} = \frac{RT}{V_A}(H2O_{Ain} - H_2O_{Aout}) \tag{11}$$

The conservation law of cathode is as Eq. (12), Eq. (13), and Eq. (14):

$$\frac{dp_{O2}}{dt} = \frac{RT}{V_C}(O_{2in} - O_{2used} - O_{2out}) \tag{12}$$

$$\frac{dp_{N2}}{dt} = \frac{RT}{V_C}(N_{2in} - N_{2out}) \tag{13}$$

$$\frac{dp_{H_2O_c}}{dt} = \frac{RT}{V_C}(\mathrm{H}_2 O_{Cin} + H_2O_{Cproduced} - H_2O_{Cout}) \tag{14}$$

In the above equations, H_{2in} represents the hydrogen inlet flow rate, O_{2in} represents the oxygen inlet flow rate, N_{2in} represents the nitrogen inlet flow rate, H_2O_{Ain} represents the anode side water inlet flow rate, and H_2O_{Cin} represents the cathode side water inlet flow rate. H_{2out} is the hydrogen outlet flow rate. O_{2out} is the oxygen outlet flow rate. N_{2out} represents the nitrogen outlet flow rate, H_2O_{Aout}

represents the anode side water outlet flow rate, and H_2O_{Cout} represents the cathode side water outlet flow rate. Among them, H_{2uesd}, O_{2used} and $H_2O_{Cprocedure}$ represent the utilization rate of gas, oxygen and water production rate respectively. These indexes are related to the output current of fuel. I is the current, as shown in Eq. (15):

$$H_{2used} = 2O_{2used} = H_2O_{Cproduced} = 2K_rI \tag{15}$$

In the Eq. (15), $K_r = N/4F$. The number of fuel cells is represented by N and the Faraday constant by F. Through this Eq. (15), the inlet flow rate and output current of each gas can be further deduced. The gas outlet flow rate is determined as Eq. (16), Eq. (17), and Eq. (18):

$$H_{2out} = (Anode_{in} - 2K_rI)\,\mathrm{P}_{\mathrm{H2}} \tag{16}$$

$$O_{2out} = (\mathrm{Cath}_{in} - 2K_rI)\,\mathrm{P}_{O2} \tag{17}$$

$$H_2O_{Cout} = (\mathrm{Cath}_{in} - 2K_rI)\,\mathrm{P}_{H_2Oc} \tag{18}$$

In the above Eq. (16), Eq. (17), and Eq. (18), $Anode_{in}$ and Cath_{in} represent the sum of anode inlet flow rate and cathode inlet flow rate respectively. P_{H2} represents hydrogen at anode side of fuel cell, P_{O2} represents oxygen measured at cathode, and P_{H2O} represents partial pressure of water vapor.

2.4 MPPT control based on former stage grid connected inverter

After the detection of the current and voltage at the voltage output end, the voltage command can be further acquired by u and represented by U_{ref}. After that, the working point of the battery is adjusted. The voltage command is subtracted from the photovoltaic inadvertent voltage value. The photovoltaic output voltage is represented by U_{PV}. Then, the input voltage of the converter is regulated by the regulator. Finally, the MPPT control photovoltaic cells are controlled. In the control of voltage outer loop and inner loop, the main application is double loop control strategy. This strategy is relatively mature. When the voltage of DC bus is controlled, the main application is the principle of power balance to effectively control the voltage outer loop. Among them, the control of the current inner loop is mainly for the real-time tracking control of the network side current.

By comparing the MPPT control of the former stage grid connected inverter with the MPPT control of the latter stage grid connected inverter, it is found that the former stage has greater advantages and can precisely achieve the control purpose. Moreover, the coupling of the front stage is very small, which can effectively control the current and voltage fluctuation and maintain its stability.

3. Results

3.1 Simulation results of fuel cell

In this study, based on the space dynamic model and voltage current model of fuel cell, the simulation model of fuel cell is further established. The fuel cell is composed of three fuel stacks in parallel, each of which has 32 fuel cells. The partial pressure of hydrogen and oxygen in the fuel cell is 0.3MP, and the external resistance of the fuel cell is also different in each time period, 3.5 Ω in 1 to 10 seconds, 2.5 Ω in 10 to 15 seconds, and 0.5 Ω in 15 to 20 seconds. The variation of hydrogen pressure, output voltage and output current at anode side of fuel cell stack are shown in Fig. 7 and Fig. 8:

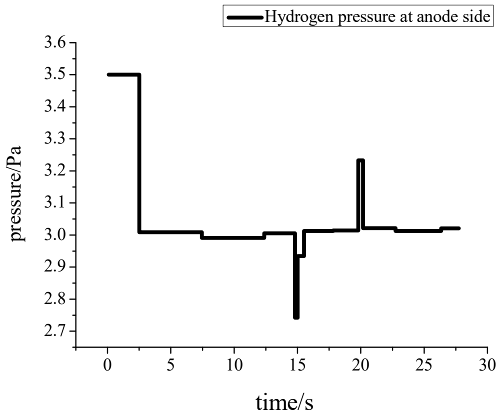
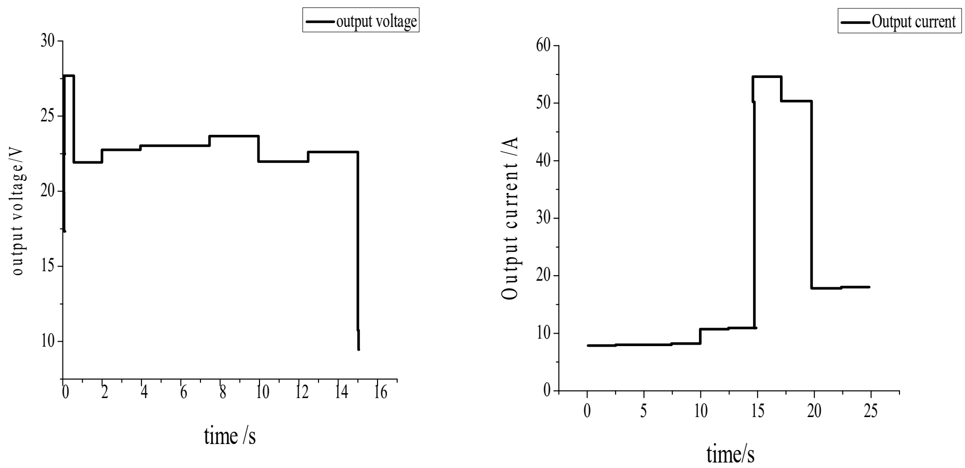


Figure 7 Change of hydrogen pressure on anode side of fuel cell stack



A(Output voltage change)

B(Output current change)

Figure 8 Changes of output voltage and current of fuel cell

According to Fig. 7 and Fig. 8 above, the hydrogen pressure on the anode side of the fuel cell can be maintained at 0.3MP at a fast speed, which shows the effectiveness and superiority of the method proposed in this study for controlling the hydrogen flow rate. In addition, according to the change curve of current and voltage in Fig. 7 and Fig. 8 above, it can be seen that the voltage of fuel cell is much smaller than the polarization voltage of fuel cell in the process of output. Its voltage decreases gradually from 14 seconds to 16 seconds. The output current of the fuel cell reaches its maximum in 15 to 20 seconds

3.2 Simulation results of control strategy

According to Fig. 9, it can be seen that there is a certain relationship between the waveform of the active power and the illumination. It can be found that the illumination changes and the active power changes with it. Moreover, the changing waveform is very similar to that of illumination, even close to each other. Once the illumination changes suddenly, the system can also accurately locate and track the maximum power point. In the case of reactive power, the system is in the state of zero.

However, its power factor is close to 1, which shows that the control of this power generation system is very superior.

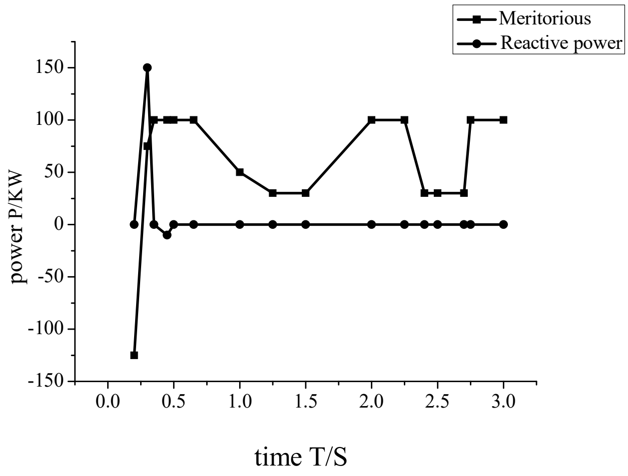


Figure 9 Reactive and active power under control strategy

4. Discussion

China's coal production is second to none in the world. In recent years, with the continuous improvement of the economic level and people's living standards, the consumption rate and utilization rate of coal resources in China are higher and higher. The application of coal resources has promoted the development of China, not only the national economy, but also people's life style has been greatly changed [12]. The safety, economic operation and clean combustion of coal-fired power generation are of great significance to the development of national economy, the improvement of people's life and the improvement of living environment. However, it also inevitably causes great damage to the environment.

In this study, by expanding the optimized design of hybrid battery storage, MPPT control algorithm and conductance increment algorithm are applied to the design of power generation system to track the maximum power of the system. In addition, the mathematical model of photovoltaic power generation and the dynamic model of PEMFC are established. Through research, it can effectively maintain the stability of photovoltaic storage system, improve its operation efficiency, and extend its service life. The simulation results show that the hydrogen pressure on the anode side of the fuel cell can be maintained at 0.3MP at a fast speed. In the process of fuel cell output, its voltage is much smaller than the polarization voltage of fuel cell, and its voltage gradually decreases in 14 seconds to 16 seconds. Once the illumination changes suddenly, the system can also accurately locate and track the maximum power point, and output the electric quantity. The experimental results show that the algorithm proposed in this study has good applicability and can be widely used in the grid connected photovoltaic power generation system, which is of great value to improve the stability and operation efficiency of the battery storage system.

5. Conclusion

Based on the mathematical model of photovoltaic power generation and the dynamic model of PEMFC, the MPPT control strategy and conductance increment method are applied to optimize the hybrid battery storage system, which can effectively promote the more efficient operation and work of the battery, improve its stability and flexibility. However, the mathematical model of photovoltaic power generation established in this study is only aimed at the dynamic model of anode and cathode and the output voltage model of fuel cell, without in-depth consideration of the water management, humidity control, temperature control and other aspects of fuel cell, which should be further studied in the future.

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