RESEARCH ON FUEL CELL BASED ON PHOTOVOLTAIC TECHNOLOGY

by

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Original scientific paper
https://doi.org/10.2298/TSCI191226134L

To investigate the hybrid thermal energy storage in photovoltaic fuel cells, a hybrid thermal energy storage control system for photovoltaic fuel cells is explored model construction and simulation. The correlations between the system components and the external factors are analyzed. The results show a positive correlation of the state of charges between the storage battery and the hydrogen storage tank at 0-15 hours, while no correlation exists between them at 15-35 hours. Meanwhile, the sunshine intensity and the photovoltaic output share a positive correlation. In summary, the hybrid thermal energy storage system is critical for photovoltaic fuel cells. The charging and discharging of the battery depends on the photovoltaic intensity. The constructed grouping management model for storage battery is outstanding and satisfies the operational requirements of photovoltaic fuel cells.

Key words: *photovoltaic, battery, storage, fuel, load*

Introduction

Due to the current shortage of fossil energy worldwide, the research on photovoltaic fuel cell (PVFC) has become the mainstream direction [1]. The efficient storage of energy of PVFC is the core and difficulty in the development of photovoltaic cells [2]. In China, the sunshine resource is rich. The way to fully integrate solar energy and other energies is the key. The photovoltaics receive sunlight and convert the solar energy into other forms of energy [3]. Whether it is for military, aerospace, industrial, or everyday purposes, solar energy can be a driving force for production. Also, solar energy is very prominent in price and cost performance; therefore, it has a very broad application prospect [4]. However, without efficient energy storage technology, the utilization of solar energy will be limited [5]. In the PVFC packs, when the sunlight is sufficient, the excess photovoltaic output is stored in the system in case there is no illumination [6].

The storage of energy is important in various fields. Therefore, the research on an efficient and stable energy storage system is indispensable [7]. Solar energy is a clean energy, which is economical and inexhaustible. Currently, the researches in the field of PVFC are still in the initial stage. Therefore, this study focuses on constructing and designing an energy storage system that satisfies the normal operation of PVFC, as well as realizing the efficient storage and output of photovoltaic energy. Thus, the research on the components of the energy storage system is necessary [8].

In this study, the mechanism between the storage battery, photovoltaic matrix, and the fuel cell is studied by simulation experiment method, and the correlation between hydrogen

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storage high pressure tube tank and storage battery is analyzed. The research results have indicated that the storage module based on PVFC is essential for photovoltaic cells. The storage battery is the protection of photovoltaic cells. The storage battery model constructed in this study satisfies the normal operation needs of PVFC. The innovation of this study mainly lies in the analysis of the core of the storage chain for PVFC. Previously, most of the researches focus on the operating system of photovoltaic cells. Therefore, this study has significant value for the subsequent research on battery storage technology.

Methodology

The PVFC

The the off-grid working mode and DC bus structure are adopted. The main components include photovoltaic modules, proton exchange membrane fuel cells, proton exchange membrane water electrolysis cells, storage batteries, hydrogen tanks, power converters and controlling devices [9]. In the system, each component is connected to the DC bus through a power converter. Photovoltaic cells are the basic units for converting solar energy into electrical energy [10]. A plurality of batteries are connected in parallel and packaged to form a photovoltaic module. The structure of photovoltaic cell power generation is shown in fig. 1. The equivalent circuit model of photovoltaic cells:

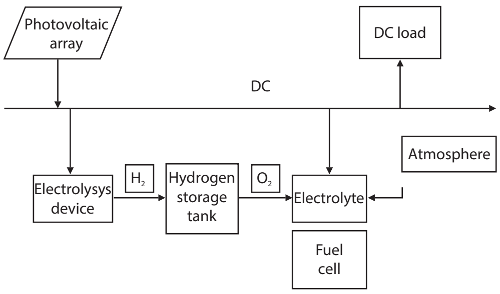

Figure 1. Structure of photovoltaic cell power generation

$$I_{\mathrm{PV}} \quad I_{\mathrm{ph}} - I_{\mathrm{sat}}\left[\exp\left(\frac{U_{\mathrm{PV}} \quad R_s I_{\mathrm{PV}}}{U_t}\right) - 1\right] - \frac{U_{\mathrm{PV}} \quad R_s I_{\mathrm{PV}}}{R_p} \tag{1}$$

where I_{PV} [A] is the output current of the battery, U_{PV} [V] – the output voltage of the battery, I_{ph} [A] – the photo-generated current, I_{sat} [A] – the reverse saturation current of the diode, and U_t [*V*]– the thermal voltage.

Fuel cell

The PEMFC reactor is composed of plural serially-packaged single bateeries. A single battery is composed of a cathode, an anode, and a proton exchange membrane between the anode and the cathode. The anode supplies hydrogen while the cathode supplies air [11]:

$$U_{\mathrm{cell}} = E_{\mathrm{nemst}} - \eta_{\mathrm{act}} - \eta_{\mathrm{ohmic}} - \eta_{\mathrm{con}} \tag{2}$$

According to the Ideal Gas Law, the pressure of the cathode P_{cath}:

$$P_{\mathrm{cath}} = \frac{\frac{1}{K_{\mathrm{O_2},c}}}{1+\tau_{\mathrm{O_2},c}s}\left(0.21F_{\mathrm{in},c} - F_{\mathrm{O_2}}\right) + \frac{\frac{1}{K_{\mathrm{N_2},c}}}{1+\tau_{\mathrm{N_2},c}s}\left(0.79F_{\mathrm{in},c}\right) + \frac{\frac{1}{K_{\mathrm{vap},c}}}{1+\tau_{\mathrm{vap},c}s}\frac{p_{\mathrm{vap},c}}{p_{\mathrm{cath}} - p_{\mathrm{vap},c}}F_{\mathrm{in},c} \tag{3}$$

According to the Ideal Gas Law, the pressure of the anode P_{an}:

$$P_{\mathrm{an}} = \frac{\frac{1}{k_{\mathrm{H_2},a}}}{1+\tau_{\mathrm{H_2},a}s}\left(F_{\mathrm{in},a} - F_{\mathrm{H_2}}\right) + \frac{\frac{1}{K_{\mathrm{vap},a}}}{1+\tau_{\mathrm{vap},a}s}\frac{p_{\mathrm{vap},a}}{p_{\mathrm{an}} - p_{\mathrm{vap},a}}F_{\mathrm{in},a} \tag{4}$$

The power consumed by the air compressor of the PEMFC cathode to provide oxygen supply:

$$P_{cp} = \tau_{cp}\omega_{cp} \tag{5}$$

where τ_{cp} [NM] is the torque of the compressor and ω_{cp} [rads^{-1}] – the rotational speed of the compressor. If the power required by the compressor is provided by the fuel cell, then the net output power of the fuel cell:

$$P_{net} = P_{syack} - p_{cp} \tag{6}$$

Electrolyzer

The basic working principle of the proton exchange membrane water electrolyzer (PEMWE) is to decompose water into hydrogen and oxygen by electricity. The PEMWE mainly consists of a thin proton exchange membrane electrolyte, a catalytic electrode, and a current collector [12]. Based on the experimental data of PEMWE, the correlation between voltage and current is described:

$$U_{elec} = E_{rev} + \frac{r_1 + r_2 T_{elec}}{A_{elec}} I_{elec} + \left(s_1 + s_2 T_{elec} + s_3 T^2{}_{elec}\right) \tag{7}$$

The production rate of hydrogen can be expressed:

$$F^{cath}_{Hy,prod} = \eta_i \frac{N_{elec} I_{elec}}{2F} \tag{8}$$

where η_i is the current efficiency of the electrolytic cell, N_{elec} – the number of single electrolytic cells, and F – the Faraday constant, and its value is 96485 C/mol.

Storage battery modelling

The battery energy storage technology is relatively mature. The representative large-capacity battery energy storage technology includes lithium battery, flow battery, and sodium-sulfur battery [13]. Due to the mature technology and low cost of lead-acid battery, it is suitable for large-scale utilization of microgrid. Therefore, this study uses the storage battery as one of the energy storage components of hibrid energy storage system [14]. The characteristic correlation between the voltage and current of a lead-acid battery during charging and discharging processes can be expressed:

$$U_{bat} = U_{oc} \pm U_{oc} R_{bat} \tag{9}$$

where U_{oc} is the open-circuit voltage and R_{bat} – the internal resistance. While being charged, the battery current is positive, which is negative while being discharged. The internal resistance R_{bat} is time-varying, depending on the battery capacity, charging/discharging current, and temperature parameters [15]. The discharging and charging processes of the battery will be modeled separately. The model takes into account the changes in the voltage, current, state of charge (SOC), and temperature parameters of the battery.

Storage battery output characteristics

The common battery charging methods include constant current charging, constant voltage charging, and stage charging. Constant current charging is to charge the battery with a constant charging current. By adjusting the charging voltage of the battery and the magnitude of the series resistance to maintain the charging current, fast charging is achieved. However, as the constant

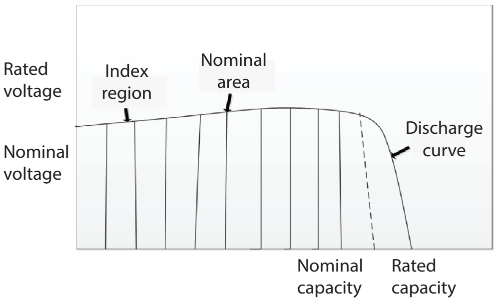

Figure. 2 Characteristics of charging and discharging

current charging progresses, the voltage at the outlet side of the battery will gradually increase, causing the charging process is difficult to control, and even the problems of overcharging and over-current. Constant voltage charging refers to charging the battery with a constant charging voltage. However, as the charging process progresses, the voltage at the outlet side of the battery will always increase. Accordingly, the charging current will always decrease, and the charging speed will be slowed down. The discharging characteristic curve is shown in fig. 2.

The discharging voltage of the storage battery:

$$U_{\text{bat}} = \left[2.085 - 0.12\left(1 - S_{\text{S0Cbat}}\right)\right] - \frac{I_{\text{bat}}}{C_{10}}\left[\frac{4}{1+\left(I_{\text{bat}}\right)^{1.3}} + \frac{0.27}{\left(S_{\text{S0Cbat}}\right)^{1.5}} + 0.02\right]\left(1 - 0.007\Delta T\right) \tag{10}$$

The stage charging method is a stage-wise charging method with first constant current charging and then constant voltage charging. It has the characteristics of a fast-charging rate and safe charging, which is often used in practical applications. First, the battery is subjected to constant current charging to set the battery terminal voltage value. Before reaching this value, the battery is charged at a constant current to meet the rapidity requirement. Then, after the voltage value is reached, the charging mode is changed from constant current to a constant voltage. Finally, considering the impact of the self-discharge of the battery, the battery is charged with a constant current in a small current. The following is the correlation between the port voltage and the current when the battery is charged stage-wise.

The charging voltage of the storage battery:

$$U_{\text{bat}} = \left[2 - 0.16 S_{\text{SoCbat}}\right] + \frac{I_{\text{bat}}}{C_{10}}\left[\frac{6}{1+\left(I_{\text{bat}}\right)^{0.86}} + \frac{0.48}{\left(1 - S_{\text{S0Cbat}}\right)^{1.2}} + 0.036\right]\left(1 - 0.025\Delta T\right) \tag{11}$$

The inductor in the bidirectional converter can transmit power efficiently and can also play a role in high-frequency filtering. It is required that the inductor current is continuous under two operating states. Then, the constraint condition that the energy storage induction is satisfied:

$$\Delta U_2 = \frac{\Delta Q}{C_2} = \frac{PDT}{C_2 U_2}, \quad \eta_u = \frac{\Delta U_2}{U_2}, \quad C_2 \ge \frac{PDT}{\eta_u U_2^2} \tag{12}$$

The breaking frequency of the inverter is set to 15 kHz. The battery is a certain product whose voltage range of outlet side is 11.7-15.4 V. The supercapacitor is a certain product whose rated capacity is 58 F and the voltage range of the outlet side is 0-20 V. The voltage range of the outlet side of the converter is 40-60 V.

The control strategy of PVFC

The operating parameters of the components in the photovoltaic system configuration scheme are accurate and rigorous. To ensure the safety, reliability, and continuity of the system, the key operational parameters of each component must be stable within the requirements. The control principle of the PVFC power generation system is shown in fig. 3. Each unit with different characteristics in the system is realized as an organic entity. The timely response to load requirements requires co-ordinated control of the system to form an effective energy management strategy.

In the energy storage management system designed in this study, the DC bus voltage is required to be around 220 V, and the maximum stability is maintained. The components remain independent and do not interfere with each other, but they maintain a close relationship with the bus. The traffic is achieved through converters, and the ultimate goal is to achieve the matching and perfection of the output between each other. Through the adjustment and control of the system, the purpose of power balance and voltage stabilization is achieved. The specific method is: the first purpose of photovoltaic power generation is to meet the working needs of the load. If the photovoltaic power generation still has surplus energy, the battery management will be stored inside the system prior to ensure the storage state of the battery. If there is still any remaining electricity at this time, the photovoltaic energy will be converted into hydrogen energy of the electrolyzed water through the work of the electrolytic cell, which will be stored in the high pressure tube to ensure that it will not leak and be lost during utilization. If the photovoltaic power generation cannot meet the normal working needs of the load, the energy of the battery will be first delivered to meet the normal working needs of the load. If the energy of the battery cannot meet the working requirements of the load, the fuel cell will be utilized to meet the working needs of the load. According to the law and requirements, the PVFC will ensure that the load can work normally, which will be operated normally regardless of the insufficient photovoltaic power generation. Also, there will be no waste of energy caused by excessive photovoltaic power generation, which forms a perfect ecosystem.

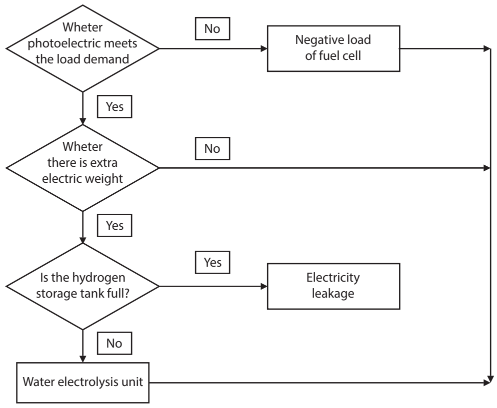

Figure 3. Controlling principles of PVFC power generation system

The priority setting of the photovoltaic module is to perform the rated output of the maximum power under the control of the system and then deliver the power into the streamline under the control of the converter to realize the current transmission. This study uses a boost type converter for current delivery. The pressure and temperature conditions at work have a great influence on the life of the system. Keeping the temperature and pressure within the set range is the best condition for maintaining work state and service life. In most cases, the temperature is required to be kept in the range of about 60 °C. As for the range of pressure, it is generally required to maintain the range of the standard atmospheric pressure, so as to maximize the working life of the system and ensure the efficient works of the system. It is also essential to ensure the normal operation of the exchange membrane. The normal operation of the exchange membrane will avoid failure. The control measures of pressure are mainly realized by the flow of hydrogen and oxygen.

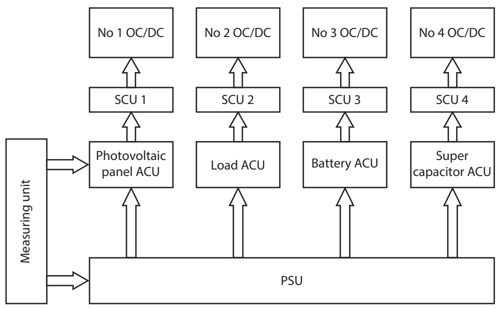

Figure 4. Independent photovoltaic power generation system control structure

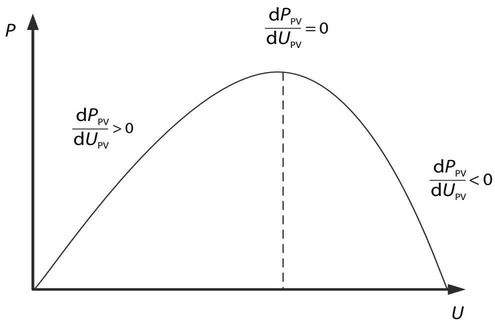

Figure 5. Conductance increment research method

Such measures are relatively safe. The control structure of the independent photovoltaic power generation system is shown in fig. 4.

In the PVFC system designed in this study, the conductance increment research method is shown in fig. 5. In this study, the battery system is divided into three groups for energy storage and transmission. The three groups are independent of each other and have no interference relationship with each other. Each group realizes the communication and the connection with the current bus through a converter, so as to ensure that they do not interfere with each other and will not cause the loss of information, resulting in a short circuit. Due to the influence of natural sunlight and other factors in the photovoltaic system, the output capacity of the photovoltaic is unstable. Therefore, the photovoltaic energy output is often interrupted. Also, the characteristics of photovoltaics are relatively random, there is no specific rules and methods for constraining and correction, which is also a prominent feature of PVFC. Therefore, for the set-up and management of the storage system in PVFC, this study first uses the grouping management for controlling and researching the system, *i. e.*, concentrating all the energy of photovoltaic pairs for a group under specific conditions at a specific time. The output work does not charge the three groups at the same time, instead, only one group is charged and transmitted separately. Until one of the groups is saturated, the other groups will be charged and managed. According to this design cycle, the transmission of photovoltaic energy ensures that the charging management of each group is independent, which not only avoids the waste of energy but also ensures the safety of the battery pack, making sure that the battery is in a state of charging and discharging. Therefore, the working time of the battery is prolonged, which is also the core idea of the battery storage model designed in this study. Through such an energy storage management system, the performance of PVFC will be greatly improved, and the further development of the photovoltaic industry will be promoted.

Dynamic simulation and performance analysis

In this study, the main components (photovoltaic modules, fuel cells, electrolytic cells, and storage batteries) of photovoltaic microgrids based on hybrid energy storage are modeled in MATLAB/SIMULINK environment. The dynamic simulation platform of the photovoltaic microgrid is built according to the network structure. While realizing the key component control strategy and the microgrid co-ordinated control strategy, the dynamic performance of the photovoltaic microgrid based on hybrid energy storage technology is analyzed.

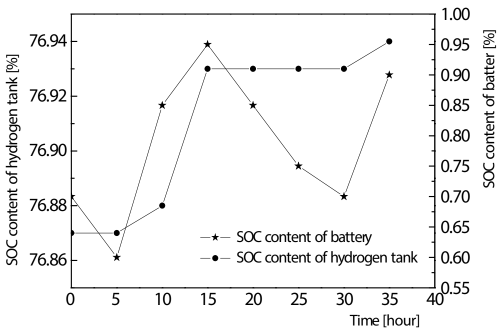

Figure 6. Statuses of battery packs and hydrogen storage tanks

Results and discussion

The states of the battery pack and the hydrogen storage high pressure tank are shown in fig. 6. The two curves represent the remaining energy management levels of the battery and the hydrogen storage tank. As shown in the data and trend graphs in the figure, the level of remaining battery power can achieve a relatively ideal state and can continue to discharge and charge for a long time. In comparison, the remaining energy management level of the hydrogen storage tank is relatively low. In addition, it can be seen that the relationship between the two sets of data lines can be divided into two-stages for analysis. The trend of the remaining energy management level of the battery and the state of the residual energy management level of the stored hydrogen in the 0-15 hours are consistent and positively correlated, *i. e.*, they are closely related to each other. The running trend of the data of the 15-35 hours group is diverging, and there is no obvious relationship between them, *i. e.*, they are independent of each other. In summary, there is a certain internal relationship between the remaining energy management level of the battery and the remaining energy management level of the hydrogen storage organ.

The energy exchange between the battery pack and the fuel cell is shown in fig. 7. The two sets of curves represent the energy exchange status of the fuel cell and the battery, respectively. As shown in the data and trend graphs in the figure, the fuel cell and the battery pack have consistent trends in 0-30 hours, sharing a positive correlation. Therefore, in 0-30 hours, they are interdependent and closely related. Within 30-35 hours, the data of the two groups are in the opposite trends, and there is no obvious internal correlation between them. In addition, when the value of the representative current is greater than 0 in the battery chart, it indicates that the photovoltaic power generation is sufficient to meet the load usage. When the value is less than 0 in the battery chart, it indicates that the current intensity is not enough. At this time, the battery is powered to meet the demand. The fuel cell strength indicates that when the battery is insufficient, the fuel cell is operating, and the operation of the load is satisfied by realizing the delivery of the current. In summary, when the photovoltaic power generation is insufficient, the battery and the fuel cell are used to supplement the power.

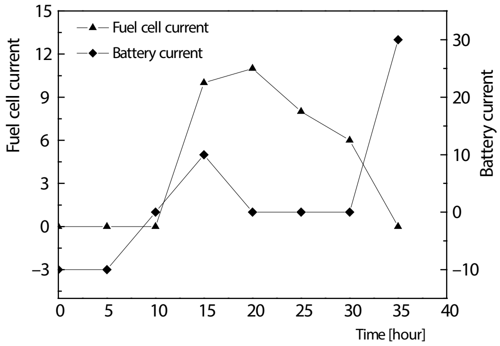

Figure 7. Energy exchange between the battery pack and the fuel cell

The relationship between sunshine intensity and photovoltaic output is shown in fig. 8. The two groups of data are relatively close to each other. As shown in the data and trend graphs in the figure, the relationship between sunshine intensity and photovoltaic output is positive. The photovoltaic output increases as the sunshine intensity increases. In summer, due to the relatively large light intensity, when the light intensity is sufficient to meet the load demand, the remaining energy will be stored in the battery to achieve later energy recycling. In winter, the light intensity is relatively small, and the daylight time becomes shorter. Therefore, the light intensity is reduced, and the output of the photovoltaic cannot meet the needs of the load. At this time, the output power of the battery is utilized to meet the needs, and the fuel cell also works to meet the current demand of the battery.

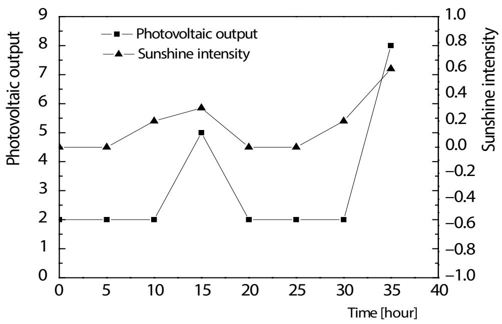

Figure 8. Study on the relationship between sunshine intensity and photovoltaic output

Conclusion

The correlations between the system components and the external factors are analyzed. The research results show that the output voltage of the fuel cell is stable when the load is sent out. However, the current fluctuation is obvious, and there is no significant relationship between them. In addition, the input power of the electrolytic cell and the current intensity and voltage of the electrolytic cell exhibit a significant positive correlation, and the data are simultaneously increased or decreased. The packet management strategy prevents the battery from being undercharged, which prolongs the service life of the battery and enables more efficient operations. The function of the battery is that when the photovoltaic power generation is insufficient and the load demand cannot be met, the battery is used to replenish the power, and the fuel cell starts to work. The relationship between sunshine intensity and photovoltaic output is basically positive. When the light intensity is sufficient for the load, the remaining energy is stored in the battery. This study also has some deficiencies in the research process, which are mainly caused by the fact that this study is in the experimental stage, many external factors are ignored, and the results may be slightly less convincing. Still, the research in this study provides a valuable reference for the research of PVFC storage systems from a qualitative perspective.

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Paper submitted: December 26, 2019
Paper revised: January 31, 2020
Paper accepted: February 15, 2020