RESEARCH ON THERMAL ENERGY CONTROL OF PHOTOVOLTAIC FUEL BASED ON ADVANCED ENERGY STORAGE MANAGEMENT

by

Xiaoqin HUANG [a*] ***and Fangming YANG*** [b]

[a] Department of Information Engineering, Guangdong Eco-Engineering Polytechnic, Guangdong, Guangzhou, China
[b] Ehv Power Transmission Company Maintenance and Test Center, China Southern Power Grid, Guangdong, Guangzhou, China

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This paper proposes a photovoltaic fuel cell power generation system to convert solar thermal energy into electrical energy after storage. The energy conversion method of the system mainly utilizes hydrogen storage to realize long-term storage of thermal energy, and realizes continuous and stable power supply through the co-operation between the micro-gas turbine and the proton exchange membrane fuel cell. Based on the model of each component, the simulation platform of photovoltaic fuel cell hybrid thermal energy storage control power generation system is built. Based on the design principle and design requirements of photovoltaic power generation system, the photovoltaic fuel cell hybrid power generation system studied in this paper has a simple capacity. Match the design and conduct thermal energy storage management research on the system according to the system operation requirements. The paper studies the management of hybrid fuel energy storage control system for photovoltaic fuel cells. The paper is based on advanced thermal energy storage management for photovoltaic prediction and load forecasting, and through the organic combination of these three layers of thermal energy storage management to complete the thermal energy storage management of the entire system. Finally, the real-time thermal energy storage management based on power tracking control is simulated and analyzed in MATLAB/Simulink simulation environment.

Key words: *hybrid photovoltaic power generation, thermal energy storage, thermal energy storage control design, simulation analysis, photovoltaic fuel cell*

Introduction

With the rapid development of the economy and the continuous improvement of living standards, people's demand for electricity is also growing. According to incomplete statistics, there are still about 1.4 billion people in the world who lack electricity. Most of these people are mainly scattered in various remote areas where the large power grid is difficult to penetrate. Therefore, if the traditional large-scale power grid is used to solve the problem of electricity consumption of such a population, it will require a very large cost and a waste of resources [1]. In addition, if a conventional distributed system of Diesel engines and batteries is used to solve such problems, it will also require a large cost (high fuel transportation cost, short battery life),

* Corresponding author, e-mail: telangpuus@qq.com

and the power generation process is not environmentally friendly. With the rapid development of new energy technologies and distributed power generation technologies in recent years, distributed power generation systems based on new energy sources have become possible to solve the problem of power consumption in remote areas. The photovoltaic (PV) fuel cell hybrid power generation system has become one of the more suitable distributed power generation systems for solving such power problems because of its almost no regional restrictions and high efficiency and environmental protection.

The PV fuel cell hybrid power generation systems are of great significance for improving the reliability of power supply and achieving energy and environmental sustainability. Its significance mainly includes:

– It can solve the problem of power supply in remote areas.
– Reduce the consumption of traditional energy sources and alleviate the energy crisis.
– Reduce air pollution and improve the environment.
– Efficient and reliable. The fuel cell is not limited by the Carnot cycle, so its power generation efficiency is high (about 40%), and the cogeneration efficiency can reach more than 80%.

Therefore, PV fuel cell hybrid power generation systems are more efficient and reliable than traditional PV power generation systems. Therefore, a hybrid system combining fuel cells with PV power generation has a very broad application prospect [2].

In the hybrid power generation system of the present invention, the PV array converts solar energy into electrical energy by using a PV effect. The hydrogen storage system stores excess electric energy for use in a proton exchange membrane fuel cell or realizes long-term storage of energy. A micro-gas turbine and a proton exchange membrane fuel cell. For the system auxiliary power supply, the power is supplied to the load when the PV power generation cannot meet the load demand or no light. The super capacitor is the power quality compensation device, which plays the role of cutting the peak and filling the valley when detecting the power fluctuation of the power grid, maintaining the micro power grid. Internal power balance and improved system stability. The hydrogen storage system mainly includes a proton exchange membrane water electrolysis tank, a power conversion device, and a hydrogen storage device. The proton exchange membrane water electrolyser (PEMWE) uses the excess electric energy of the hybrid power generation system to produce hydrogen through water electrolysis to realize the conversion of electric energy and hydrogen energy. The hydrogen storage device (such as high pressure hydrogen storage tank) stores hydrogen to realize long-term storage of hydrogen energy and the proton exchange membrane fuel cell (PEMFC) utilizes hydrogen storage device. Hydrogen converts hydrogen energy into electrical energy through an electrochemical reaction achieve hydrogen energy-electric energy conversion. In this way, the co-operation between the hydrogen storage device and the PEMFC not only realizes the storage of electric energy but also forms a cycle of electric energy-hydrogen energy-electric energy, which improves the sustainability of the system [3]. When micro-turbine and PEMFC work, a large amount of heat energy is generated. Therefore, a waste heat recovery system is configured for the hybrid power generation system, and the waste heat generated by the hybrid power generation system during power generation is recovered and supplied to the heat load, thereby realizing energy through electric heating and heat supply. Step-by-step utilization improve the energy efficiency of hybrid power generation systems. In addition, due to the energy cycle formed between PEMFC and PEMWE, and the cycle process has a certain degree of energy loss, the two units cannot work at the same time, avoiding waste of energy.

Design of PV fuel cell hybrid power generation system

The PV battery model

The so-called PV cell is a conversion device that directly converts light energy into electrical energy based on the PV effect of semiconductor *P-N* junction receiving sunlight. The core of a typical silicon material PV cell is the semiconductor material *N*-type silicon and *P*-type silicon. When the *N*-type silicon and the *P*-type silicon are in contact, a *P-N* junction is formed at the contact, and a built-in electric field is formed in the junction region, and the direction is directed from the *N*-type region the *P*-type region. It is known from physics that when solar photons are incident on the surface of a semiconductor, the photon energy is absorbed by the semiconductor, and the electrons in the lower energy valence band are ex-cited, and the energy gap becomes a free electron in the higher energy conduction band. Forming a charged cavity in the valence band. After the previous excitation, a large number of electron-hole pairs in a non-equilibrium state are generated inside the semiconductor material, and the carrier of the *P-N* junction is pulled to the other region by the pulling action of the carrier, and a photoelectromotive force opposite to the electric field of the *P-N* junction barrier is formed externally. This is the PV effect. The principle is shown in fig. 1.

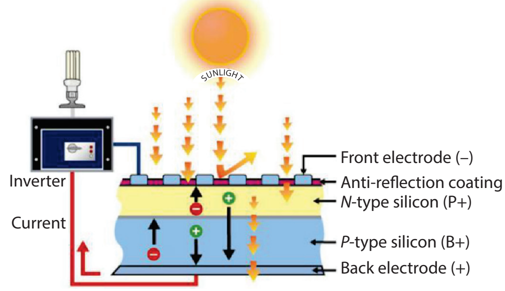

Figure 1. How PV cells work

Equivalent circuit

The equivalent circuit of a typical single crystal or polycrystalline PV cell can be described in figure. The current source is represented by the photocurrent, I_{ph}, generated by the PV cell, and the total diffusion current through the *P-N* junction is I_D. The inherent resistance of the battery (such as bulk resistance, surface resistance*, etc.*) is represented by a series resistor R_S, and the process resistance of the battery (such as internal defects) The resulting resistance*, etc.*, is represented by a shunt resistor R_P, and a current I_{PV} flows through the load resistor R_L. In an ideal battery, R_S is small and R_P is large [4], as shown in fig. 2.

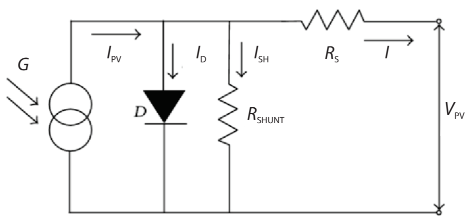

Figure 2. The PV cell equivalent circuit

The PV battery model

In the case of environmental factors (irradiance, temperature), the current-voltage characteristics of PV cells can be expressed:

$$I_{PV} = I_{ph} - I_{sat}\left[\exp\left(\frac{V_{PV}+R_s I_{PV}}{V_t}\right)-1\right]-\left(\frac{V_{PV}+R_s I_{PV}}{R_p}\right) = I_{ph}(G_a,T_c) - I_D(G_a,T_c) - I_p(G_a,T_c) \quad (1)$$

where I_{ph} [A] is the photo-generated current, I_{sat} [A] – the reverse saturation current of the diode, R_P and R_S [Ω] are the parallel and series resistances, respectively, I_{PV} [A], V_{PV} [V] – the output current (voltage) of the PV cell, n – a constant factor, q $1.6 \cdot 10^{-19}$ [C] – the electron charge,

k 1.38 · 10^{-23} [JK^{-1}] – the Boltzmann constant, I_D, I_P [A] – the current through the diode, R_P, G_a [Wm^{-2}] – the light intensity, T_c [K] – the battery temperature. Generally, the parallel resistor R_P is relatively large, and the bypass current tends to zero, so it can be ignored, and its equivalent circuit can be simplified:

$$I_{\mathrm{PV}} = I_{\mathrm{ph}} - I_{\mathrm{sat}}\left[\exp\left(\frac{V_{\mathrm{PV}} + R_s I_{\mathrm{PV}}}{V}\right) - 1\right] = I_{\mathrm{ph}}(G_a, T_c) - I_{\mathrm{D}}(G_a, T_c) \tag{2}$$

The PV equation solving

Equation (2) is a transcendental equation that is difficult to solve directly using analytical methods, but it can be solved by dichotomy, Secant or Newton iteration. The Newton iteration method, also known as the tangent method, is a common method for solving numerical values. The design principle, shown in fig. 3, is: solve the solution of equation $f(x) = 0$; let x_i be a guess solution near the exact solution; pass $[x_i, f(x_i)]$ as the tangent of $f(x)$, the tangent equation is $y = f(x_i) + f'(x_i)(x - x_i)$, and the focal equation of tangent and x-axis is $f(x_i) + f'(x_i)(x - x_i) = 0$, the solution of this intersection equation is $x_{i+1} = x_i - f(x)/f'(x_i)$, which is the Newton iteration formula for solving the approximate solution of equation $f(x) = 0$.

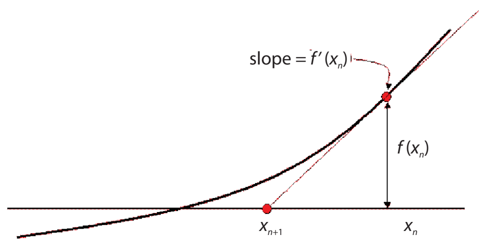

Figure 3. Newton iteration method schematic

The specific steps of using the Newton iteration method are:

– transform eq. (2) into:

$$f(I_{\mathrm{PV}}) = I_{\mathrm{PV}} - (I_{ph} - I_D) \tag{3}$$

– solve the derivative: $f'(I_{\mathrm{PV}})$ of $f(I_{\mathrm{PV}})$
– take the initial value: $I_{\mathrm{PV}}(i) = I_{\mathrm{PV}}(0)$
– substituting $I_{\mathrm{PV}}(i)$ into the following formula and finding $I_{\mathrm{PV}}(i + 1)$:

$$I_{\mathrm{PV}}(i+1) = I_{\mathrm{PV}}(i) - \frac{f[I_{\mathrm{PV}}(i)]}{f'[I_{\mathrm{PV}}(i)]} \tag{4}$$

– determine if $f[I_{\mathrm{PV}}(i + 1)]$ meets the accuracy requirements.

When it is reached, iteration is stopped. If it is not reached, it returns to the previous step to continue iteration.

The PV cell characteristics analysis

In the process of establishing the aforementioned PV cell model, we can see that the output of the PV cell has non-linear characteristics, and its output has a large time-varying effect due to weather factors such as irradiance and temperature. Based on the characteristics of the PV cells and the experimental data of commercial PV cells, a simulation model of the PV array was constructed using MATLAB/Simulink, as shown in fig. 4.

Fuel cell analysis

The theoretical maximum energy that a fuel cell can achieve is equal to the amount of change in Gibbs free energy, because its maximum theoretical efficiency (thermodynamic efficiency):

$$\eta_{fc,\max} = \frac{\Delta G}{\Delta H} \times 100\% \tag{5}$$

Under ideal conditions, if all the energy of hydrogen is converted into electrical energy, the electromotive force E [V] calculated from the high calorific value, $\Delta H = -288.84$ kJ/mol, of hydrogen:

$$E = \frac{-\Delta H}{2F} = 1.48V \tag{6}$$

This is the battery voltage of the battery under ideal conditions. Under normal operating conditions, the voltage loss must exist, and the actual efficiency of the battery η_{fc}:

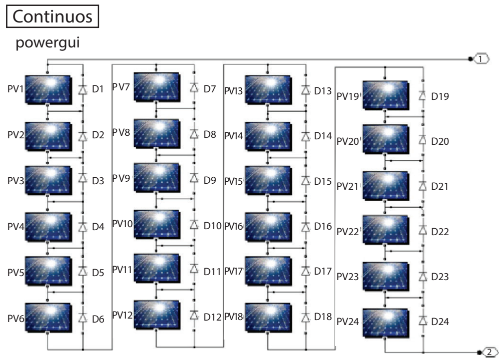

Figure 4. The PV array model

$$\eta_{fc} = \mu_{fc} \frac{V_{\text{cell}}}{1.48} \times 100\% \tag{7}$$

$$\mu_{fc} = \frac{m_{H,th}}{m_{H,\Delta ct}} \tag{8}$$

where μ_{fc} is the fuel utilization rate, $m_{H,th}(m_{H,\Delta ct})$ [kmols^{-1}] – the theoretical value (actual value) of the hydrogen gas-flow. In general, μ_{fc} is between 40% and 60%.

Thermal model

The energy loss of the fuel cell during the chemical reaction will eventually end up in the form of thermal energy through the bipolar plates and eventually reach the surrounding air and coolant in convection [5]. If the entire fuel cell stack is considered as a whole, the conduction phenomenon in the bipolar plate is neglected, and the bipolar plate is an isothermal body. The PEMFC stack temperature T_{stack}:

$$\frac{\mathrm{d}T_{\text{stack}}}{\mathrm{d}t} = \frac{1}{M_{FC}c_{P,FC}} \left[\underbrace{Q_{\text{loss}}}_{\text{energy loss}} + \underbrace{m_{CL}c_{P,CL}(T_1 - T_2)}_{\text{force ineternel convection}} - \underbrace{k_{FC}(T_{\text{stack}} - T_{\text{amb}})}_{\text{natural convection}} \right] \tag{9}$$

where M_{FC} [kg] is the mass of the stack, $c_{P,FC}$ [Jkg^{-1}K^{-1}] – the equivalent heat capacity ratio of the stack, Q_{loss} – the energy loss, m_{CL} [kgs^{-1}] – the flow rate of the cooling water, $c_{P,CL}$ [Jkg^{-1}K^{-1}] – the cooling water equivalent heat capacity ratio, T_1, T_2 [K] – the temperature before and after the cooling water enters the stack, k_{FC} [WK^{-1}] – the natural convection coefficient of the stack, and T_{amb} [K] – the air temperature around the system.

The heat inside the fuel cell mainly includes the entropy loss when a chemical reaction occurs, the chemical energy consumed by H^+ ions and oxygen to overcome overvoltage conduction, and the latent heat of water during vaporization and concentration [6]. The heat exchange Q_{phase} that occurs during the vaporization or concentration of water can be determined by the product of the vaporization or concentration of latent heat h_{fg} and the rate of change m_{phase} of the aqueous phase:

$$Q_{\text{phase}} = m_{\text{phase}} h_{fg}, \begin{cases} Q_{\text{phase}} > 0 & \text{condensation} \\ Q_{\text{phase}} < 0 & \text{evaporation} \end{cases} \tag{10}$$

In the fuel cell power generation process, the amount of water concentration or vaporization is relatively small compared to several other heat sources, so the amount of change in thermal energy caused by the change in the water phase can be ignored. The energy loss Q_{loss}:

$$Q_{\text{loss}} = \frac{-\Delta H}{2F} - V_{fc} I_{fc} = \underbrace{\frac{-\Delta H}{2F} - E_{\text{Nernst}} I_{fc}}_{\text{entropy loss}} + \underbrace{(\eta_{\text{act}} + \eta_{\text{ohmic}} + \eta_{\text{con}}) I_{fc}}_{\text{overpotential loss}} \tag{11}$$

where ΔH [Jmol^{-1}] is enthalpy change. The stack outlet temperature T_2 of the cooling water is determined by the heat of the cooling water in the cooling passage. This mandatory convection process can be expressed:

$$T_2 = T_{\text{stack}} - (T_{\text{stack}} - T_1)\exp\left(-\frac{A_c h_{FC}}{m_{CL} c_{p,CL}}\right) \tag{12}$$

where A_c [cm^2] is the area of the cooling channel, h_{FC} [Wm^{-2}K^{-1}] – the internal convection coefficient of the battery.

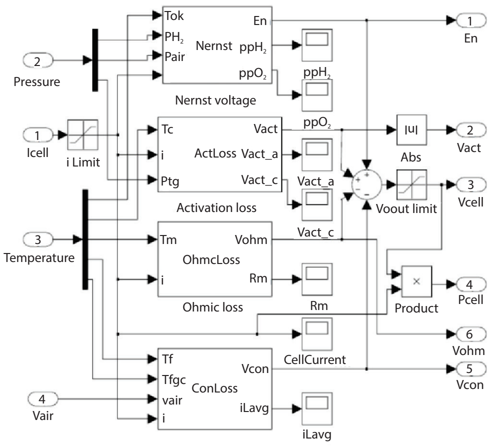

Figure 5. The PEMFC system simulation model

Analysis of fuel cell characteristics

Based on the aforementioned established PEMFC mathematical model, the simulation model of PEMFC system is built in the MATLAB/simulink simulation environment. The system model block diagram is shown in fig. 5. The model includes electrochemical models, cathode and anode models, and thermal models. In the system considered herein, the air (oxidant) required for the fuel cell is continuously supplied by the air compressor, and the hydrogen required for the anode is supplied by the high pressure hydrogen tank. When the hydrogen in the high pressure tank continuously supplies fuel to the anode, the pressure difference between the cathode and the anode should be kept at a minimum to avoid cracking of the membrane due to excessive pressure difference between the two sides of the membrane.

For PEMFC, battery performance is related to conditions such as battery operating temperature and pressure when the relative humidity of the gas is constant at 100%. Based on the PEMFC simulation system shown in fig. 5, its steady-state characteristics are shown in fig. 6.

As can be seen from figs. 6(a) and 6(b), when the battery temperature is constant, the output performance of the battery increases as the operating pressure increases. However, as the pressure continues to increase, the performance of battery performance is getting smaller and smaller. Moreover, as the pressure increases, the sealing difficulty of the battery increases greatly, and the increase in pressure also increases the power consumption of the air compressor and the fuel compressor [7]. Therefore, for a general PEMFC, the working pressure of the reaction gas is generally selected from atmospheric pressure to several atmospheres. The rated gas pressure in this system is P_{cath} = 1 atm, P_{an} = 1.5 atm.

It can be seen from figs. 6(c) and 6(d) that the PEMFC gradually increases with the temperature of the battery when the operating pressure is constant. The output performance of

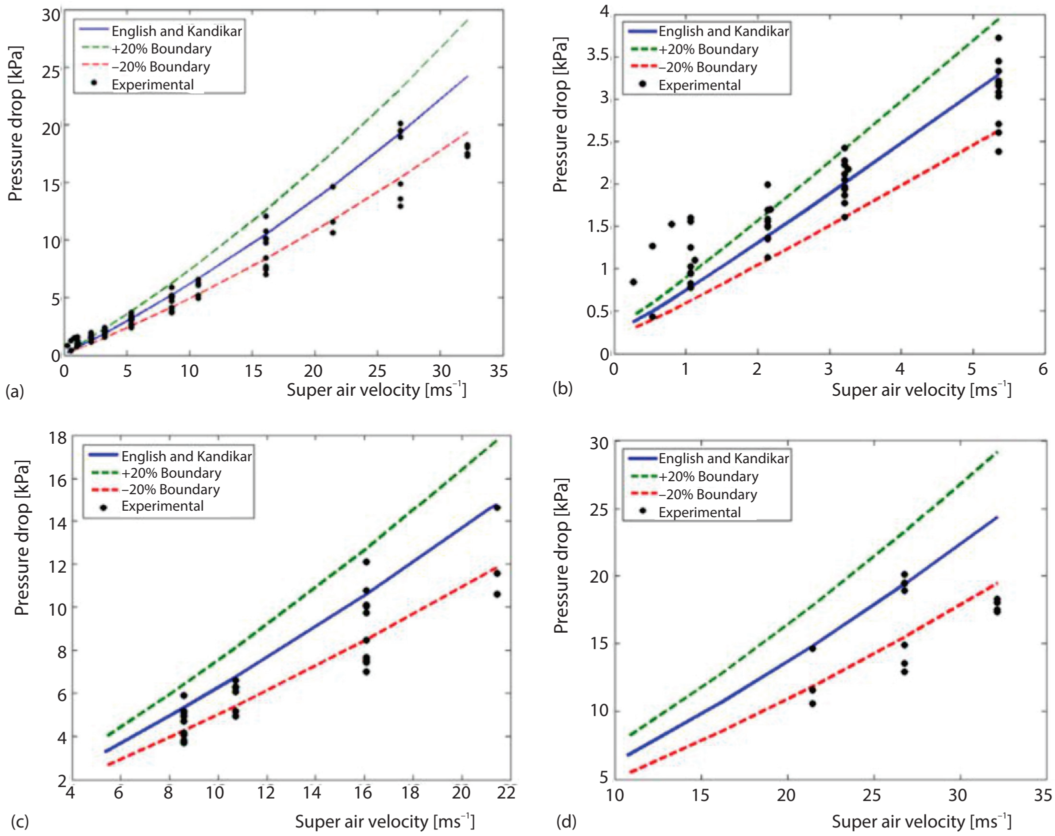

Figure 6. The PEMFC simulation characteristics

the battery also increases. Because for PEMFC, electrochemical and kinetics play a leading role, as the temperature of the battery increases, electrochemical oxidation of hydrogen and electrochemical reduction of oxygen accelerate and reduce chemical polarization. In addition, as the temperature of the battery increases, the conductivity of the proton exchange membrane can also be increased, and the ohmic polarization of the membrane can be reduced. However, since most PEMFC currently use nation membranes, this membrane must have water in the presence of protons, and at the same time as the temperature of the battery increases, at a fixed reaction gas pressure, due to the partial pressure of water vapor. The increase will inevitably lower the pressure of the reaction gas. Therefore, the current operating temperature of PEMFC using nation film is between 50 °C and 80 °C. The rated operating temperature of the PEMFC in this system is 70 °C.

Microturbine model and simulation research

The mathematical model of the micro-gas turbine is a set of mathematical equations representing various thermal processes of the micro-gas turbine. The mathematical equations representing the thermal processes of the various components of the micro-gas turbine are given below. To facilitate the analysis of the problem, the following assumptions are made during the analysis of the thermal process:

– Both air and flue gas are assumed to be ideal gases, and the fuel of the micro-gas turbine is hydrogen. In the calculation, the thermal property parameters of hydrogen are replaced by the thermal properties of pure methane.
– The system operates under normal conditions, considering only the quasi-static process of the system, regardless of the start, stop and other various fast dynamic processes of the system.
– The steady-state equation is used for thermal process analysis, ignoring the energy storage and energy transfer lag of the various components of the micro-gas turbine.
– The flow of fluid in the unit is a 1-D flow, ignoring the flow kinetic energy and potential energy of the fluid at the inlet and outlet of the unit.

Intake pipe

The intake pipe refers to a section of pipe from the gas turbine air inlet to the compressor inlet. In the design of many micro-gas turbines, this pipe also plays the role of cooling the generator. The air absorbs the heat generated by the generator during the power generation process, and the temperature rises, thereby maintaining the temperature of the generator relatively stable during power generation. At the same time, the intake pressure will decrease due to the flow resistance. This temperature rising and depressurizing process can be expressed:

$$Q_{0-1} = G_a(h_1 - h_0) \tag{13}$$

$$P_1 = P_0 - \xi_{0-1}\frac{G_a^{\ 2}}{2\bar{\rho}_{a,0-1}} \tag{14}$$

where ξ_{0-1} is the resistance coefficient of the pipe segment, which includes both the resistance along the path and the local resistance, $\bar{\rho}_{a,0-1}$ – the average density of air in the pipe segment, P_0 – the equal to the atmospheric pressure P_{atm}, where P_{atm} – the standard atmospheric pressure, h_0 – the inlet air of the micro-gas turbine depreciation, which can be calculated from the ambient temperature. According to eq. (14), the compressor inlet air enthalpy h_1 can be calculated:

$$h_1 = h_0 + \frac{Q_{0-1}}{G_a} \tag{15}$$

From the enthalpy h_1 and the function relationship between enthalpy and temperature, the air temperature T_1 at the compressor inlet can be calculated by iteration.

Thermal energy storage

The thermal energy storage device is an energy-saving device of the micro-gas turbine, which uses high temperature exhaust gas to preheat the intake air, thereby reducing fuel consumption and improving the thermal efficiency of the system. An important measure of thermal energy storage performance is the heat recovery of the thermal energy storage, which is defined:

$$\sigma = \frac{T_3 - T_2}{T_5 - T_2} \tag{16}$$

From eq. (16), T_3 can be calculated:

$$T_3 = T_2 + \sigma(T_5 - T_2) \tag{17}$$

The heat of regeneration of the thermal energy store can be calculated:

$$Q_R = G_a(h_3 - h_2) = G_g(h_5 - h_6)\eta_R \tag{18}$$

where η_R is the adiabatic efficiency of the thermal energy store, which characterizes the amount of heat loss from the thermal energy storage to the surrounding environment. From the aforementioned formula, the enthalpy h_6 after the exhaust gas passes through the thermal energy storage can be calculated.

Simulation result analysis

To verify the accuracy of the proposed model, the model was validated using operational data from a commercially available micro-gas turbine. The commercial unit is a three-phase 480VAC/30 kW unit. The maximum net output power of the unit is 28 kW, the designed speed is 96000 rpm, and the maximum inlet temperature of the turbine is 1116 K. The thermal efficiency of the unit in the design condition is (based on high calorific value). Based on the manufacturer's design parameters, the micro-turbine was simulated using the mathematical model of this paper. Figure 7 is a comparison between the simulated fuel consumption and the experimentally measured fuel consumption. Figure 7 shows that the simulation results are consistent with the trend of the experimental results. As the output power increases, the fuel consumption increases almost linearly [8]. However, fig. 7 also shows that the simulated fuel consumption is generally smaller than the actual fuel consumption, mainly because the fuel is pure methane in the model calculation, and the fuel in the experiment is hydrogen. Although the main component of hydrogen is methane, the methane content is generally only about 90%, so the experimental measurement data will be larger than the simulated fuel consumption. The dotted line in fig. 7 is the correction result after dividing the simulation data by 0.9, and the corrected result is in good agreement with the experimental data.

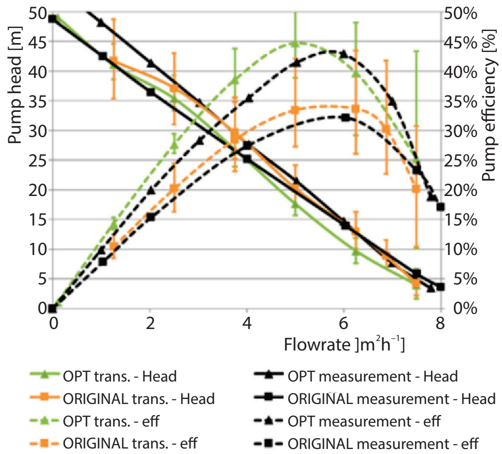

Figure 7. Comparison between measured speed and simulated speed

Conclusion

At present, the PV fuel cell hybrid power generation system is still in the demonstration operation stage, and there are still many problems to be solved in order to realize commercialization and large-scale application. This paper tries to do some work on system modelling, thermal energy storage management*, etc.*, but in the future, it still needs more in-depth research in many aspects, including improving the system simulation model and modeling method:

- In this paper, some simplifications and assumptions are made in the modelling process. There is still a lot of work to be done in developing a model that comprehensively, quickly and truly reflects the actual power generation system. It is necessary to refine the mechanism model of the system and study the system with better performance.
- According to the established thermal energy storage management method, the system complete thermal energy storage management strategy in MATLAB or other simulation en-

vironment, and compare with other energy management strategies to further explore the impact of thermal energy storage management on the overall performance of the system.

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