OPTIMIZATION OF FUEL CELL THERMAL MANAGEMENT SYSTEM BASED ON BACK PROPAGATION NEURAL NETWORK

by

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Original scientific paper
https://doi.org/10.2298/TSCI2104975G

Two thermal management control strategies, namely flow following current and power mode and back propagation neural network auto-disturbance rejection method, were proposed to solve significant temperature fluctuation problems, long regulation time, and slow response speed in fuel cell thermal management system variable load. The results show that the flow following current and power control strategy can effectively weaken the coupling effect between pump and radiator fan and significantly reduce the overshoot and adjustment time of inlet and outlet cooling water temperature and temperature difference reactor. Although the control effect of the neural network and strategy is insufficient under maximum power, the overall control effect is better than that of the flow following the current control strategy.

Key words: *control strategy, back propagation neural network, thermal management system, fuel cell*

Introduction

Proton exchange membrane fuel cell (PEMFC) is a non-linear and strongly coupled complex dynamic system with high efficiency, low noise, fast startup, and long life. It is especially suitable for the mobile power supply or distributed a small power supply. The thermal management control strategy of fuel cells affects fuel cells' dynamic performance and life and is critical to the cells' critical technologies. The operating temperature of the electric reactor is an essential parameter of the PEMFC system. The temperature distribution of fuel cells significantly influences gas pressure, humidity, the water content of proton exchange membrane, catalyst activity, chemical reaction rate, output performance, and life of electric reactor [1]. As the fuel cell, the thermal management system has its time-delay characteristics. The operating conditions (startup, acceleration, deceleration, shutdown*, etc.*) and operating conditions of the fuel cell system are relatively complex. The thermal management system's control effect is crucial to improve the reliability and operation performance of the fuel cell. The fuel cell thermal management system should ensure that the fuel cell can heat up quickly, start up as soon as possible at low temperature, and control the electric reactor's operating temperature within the efficient working range (generally 60~80 °C) at high temperature. When the temperature difference inside the electric reactor is too large, local condensation will occur in the flow passage,

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so the temperature difference between the inlet and outlet of the electric reactor's cooling water should be controlled within 5~7 °C.

Because of the shortcomings of traditional temperat ure control methods, this paper proposes a control strategy of cooling water flow following current and power, radiator fan flow following cooling water flow in the radiator, and a neural network active disturbance rejection control method to study cooling water flow and radiator fan flow. The control strategy's simulation results are compared with the experimental data to verify the correctness and effectiveness of the control model.

Fuel cell thermal management system

The fuel cell thermal management system includes the radiator, cooling water pump, thermostat, circulating cooling water pipe-line*, etc.*, and its working principle is shown in fig. 1. Within a specific temperature range, the thermostat automatically distributes the cooling water flow of each branch of the thermal management system according to the cooling water temperature to realize the rapid heating of the electric reactor in the low temperature startup stage of the fuel cell and reduce the parasitic loss of the thermal management system [2].

Circulating pump and radiator temperature control is the principal executive body. The primary pump control electric pile of inward and outward cooling water temperature difference, which rely on the circulation of the cooling water will internal heat out of the fuel cell. The radiator is the primary control electric reactor inlet temperature of cooling water, relying on a cooling fan-forced air convection cooling water cooling. Thermal management system with time delay, great inertia and non-linear characteristics, and the water pump and a cooling fan control have strong coupling effect, thereby pile in a pile load dynamic temperature fluctuation is enormous, even short of high temperature and long time adjustment may happen, this situation is not conducive to the everyday work of the pile performance of the play, will shorten the fuel battery life. Therefore, in the process of reactor work, especially in load dynamic change, we need to adopt appropriate thermal management system control strategy to ensure the stability of temperature, and to some extent, weaken the coupling effect between circulating pump and cooling fan to ensure the durability of the system and the safety margin of temperature oversetting [3]. After the cooling water circulates through the electric reactor, the cooling water temperature rises and cools down after flowing through the radiator. Moreover, the circulating cooling water pump is driven by a three-phase motor controlled by a frequency converter. The inlet cooling water temperature and inlet and outlet temperature difference of the reactor is the thermal management system's control targets.

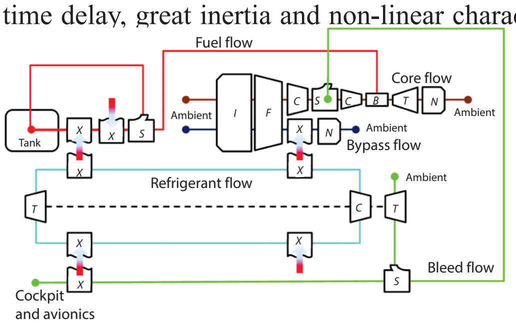

Figure 1. The PEMFC thermal management system model block diagram

Control strategy research

Principle of flow following control strategy

The flow following the current control strategy is shown in fig 2. The I_{st} is the reactor current. This control strategy combines PID control and follows control to realize partial decoupling of radiator fan and pump and rapid change of reactor temperature and steady-state stability when the battery is under variable load. Feed-forward control is used for inlet temperature

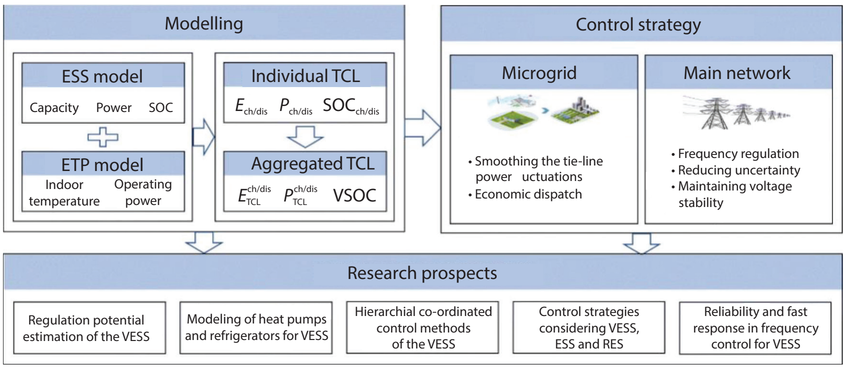

Figure 2. Control strategy principle

and inlet and outlet temperature difference of the electric reactor's cooling water. The voltage of the cooling fan is still controlled by the PID controller [4]. The water pump frequency is adjusted according to the electric reactor's current through flow following the current function realize the current following.

In the current and power control strategy, the flow follows both the present and the power. The I_{st} is the reactor current and P_{st} is the reactor power. Two feed-forward rules are adopted here. Namely, the radiator fan's flow is regulated by the flow following the cooling water heat dissipation power function in the radiator branch. The flow governs the frequency of the water pump, following the current and power position simultaneously. The simultaneous control of cooling water flow is based on the current real-time current and power values of PEMFC for fast and stable adjustment to maintain the temperature difference between the inlet and outlet of the reactor cooling water. Radiator fan flow following control is based on the cooling water cooling power value in the radiator branch to achieve fast and stable regulation ensure the cooling water's stability inlet temperature of the electric reactor [5].

Principle of back propagation neural network adRC strategy

The back propagation (BP) neural network active disturbance rejection control strategy is shown in fig. 3, and the neural network model is used to replace the non-linear error feedback control law. The control objects are the water pump and the radiator fan. To arrange the transition process of the input signal, extended state observer, the output signal of the controlled objects tracking observation, the transition of the input signal signals and the output signal tracking observation of difference as the input of the neural network model, and the neural network model of the output signal and form the system disturbance observation signal estimation compensation as the input of the object [6].

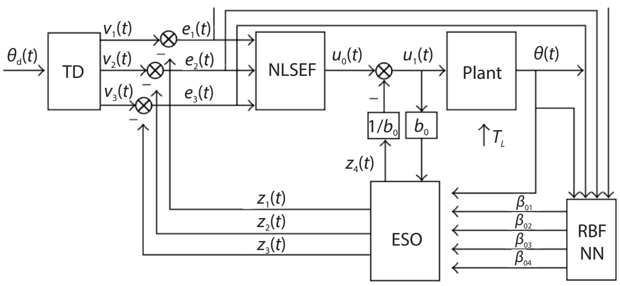

Figure 3. The ADRC strategy of neural network

Calculation of flow following function

According to the heat balance equation $Q = CM\Delta T$, the heat balance relationship of the fuel cell:

$$C_{st} M_{st} \frac{\mathrm{d}T_{st}}{\mathrm{d}t} = Q_{\text{gen}} - Q_{\text{dis}} \tag{1}$$

Thermal analysis of fuel cell system

Assuming that all the chemical energy in the fuel cell is converted and only electrical and internal energy is converted, the thermal power of the fuel cell can be calculated more accurately:

$$Q_{\text{gen}} = q_{\text{theo}} - q_{\text{elec}} \tag{2}$$

The energy inside the electric reactor is expressed as the enthalpy change between the reactants and the products in the chemical reaction process:

$$\mathrm{H}_2 + \frac{1}{2}\mathrm{O}_2 \rightarrow \mathrm{H}_2\mathrm{O}\Delta H = 285.8\ \text{kJ/mol} \tag{3}$$

Heat dissipation analysis of fuel cell system

Let us assume that the hydrogen that is not involved does no affect the system. The fuel cell system's heat transfer only considers the heat dissipated by gas and generated water and cooling water. The heat dissipation power of the fuel cell system per unit time:

$$Q_{\text{dis}} = q_{\text{sens}} + q_{\text{cool}} + q_{\text{rad}} \tag{4}$$

where q_{sens} is the sum of the heat dissipation power of the anode gas and water and the heat dissipation power of the cathode gas and water:

$$q_{\text{sens}} = q_{\text{sens,an}} + q_{\text{sens,ca}} \tag{5}$$

According to the heat balance equation, the cooling water heat dissipation power:

$$q_{\text{cool}} = W_{cl} C_{p,\mathrm{H_2O},L} \left(T_{st} - T_{\text{st,in}} \right) \tag{6}$$

The cooling water temperature at the radiator inlet and the cooling water temperature at the reactor outlet are the same as that at the reactor outlet:

$$T_{\text{heat,sin}k\text{,in}} = T_{st\text{,out}} = T_{st} \tag{7}$$

The radiator temperature is the average of the inlet and outlet cooling water temperature of the radiator:

$$T_{\text{heat,sin}k} = \frac{T_{st} + T_{\text{heat,sin}k\text{,out}}}{2} \tag{8}$$

The heat balance relationship of the radiator:

$$\rho_w V_{\text{heat,sin}k} C_{p,\mathrm{H_2O},L} \frac{\mathrm{d}T_{\text{heat,sin}k}}{\mathrm{d}t} q_{\text{cool,heat,sin}k} - q_{\text{fan}} \tag{9}$$

The radiator fan realizes the exchange of heat between the circulating cooling water and the ambient air. The cooling power of the radiator fan:

$$q_{\text{fan}} = W_{\text{fan}} C_{p,\text{air}} \left(\frac{T_{st} + T_{\text{heats in}\,k\text{,out}}}{2 - T_{\text{atm}}} \right) \tag{10}$$

Neural network AdRC model

According to eqs. (9) and (10), the thermal management system equation of the reactor can be obtained:

$$\frac{\mathrm{d}T_{st}}{\mathrm{d}t} = \frac{\dfrac{\Delta H N_{\mathrm{cell}} I_{st}}{(2F) - q_{\mathrm{elec}} - q_{\mathrm{sens}} - q_{\mathrm{rad}}}}{C_{st} M_{st}} \times \frac{C_{\mathrm{p,H_2O},L}(T_{st} - T_{st,\mathrm{in}})Q_1(1-s)}{C_{st} M_{st} n_1 p} f \tag{11}$$

According to the idea of ad RC, we take $x_1 = T_{st}$ and write the acceleration acting on the system:

$$f_{\mathrm{total}}(x_1, t) = \frac{\dfrac{\Delta H N_{\mathrm{cell}} I_{st}}{(2F) - q_{\mathrm{elec}} - q_{\mathrm{sens}} - q_{\mathrm{rad}}}}{C_{st} M_{st}} \tag{12}$$

This acceleration is part of the *total disturbance*. The specific form of the *total disturbance* is not taken into account in AdRC. Disturbance compensation can eliminate it, which is one of the advantages of AdRC. In the power reactor thermal management system, the gain of the control variable is expressed:

$$b_0 = -\frac{C_{\mathrm{p,H_2O},L}(T_{st} - T_{st,\mathrm{in}})Q_1(1-s)}{C_{st} M_{st} n_1 p} \tag{13}$$

Simulation results and analysis

Model validation

Thermal management system model validation

The cooling water flow is a constant value, and the current reactor steps from 80 A to 40 A. The temperature difference between the inlet and outlet of the reactor cooling water is simulated and compared with the experiment. Under the step change of current, the simulation value of temperature difference between the inlet and outlet of cooling water of the electric reactor is close to the experimental results. The variation trend is consistent, as shown in fig. 4, indicating that the model can reasonably simulate the heat production of the experimental electric reactor and predict the temperature of the inlet and outlet cooling water of the electric reactor [7].

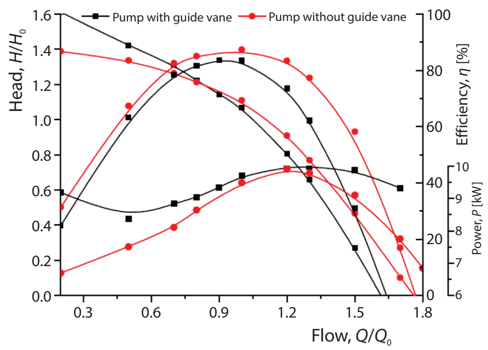

Figure 4. Changes in cooling water flow over time

Verification and simulation of control model of the thermal management system

The experimental parameters are the same as those in the first experiment, as shown in tab. 1. The change in cooling water flow over time is shown in fig. 4. A is flow following the current control strategy in the figure, *B* is a neural network active disturbance rejection control strategy, and *C* is flow following current and power control strategy simultaneously. Control strategy *A* is the same as the experimental control strategy [8]. Under the condition of the step change of reactor current, the variation trend of the simulation value of cooling water flow is consistent with the experimental results, and the relative error is within 3%. The controlled circulation pump can quickly and steadily adjust the cooling water flow to a reasonable value and improve the response speed and accuracy of cooling water flow to the change of fuel cell reactor heat production.

Table 1. Control experimental parameters of the thermal management system

Parameter	The numerical
Inlet cooling water temperature of electric reactor [°C]	60
Cooling water temperature [°C]	5.5
Change in current [A]	18-25 to 28-30

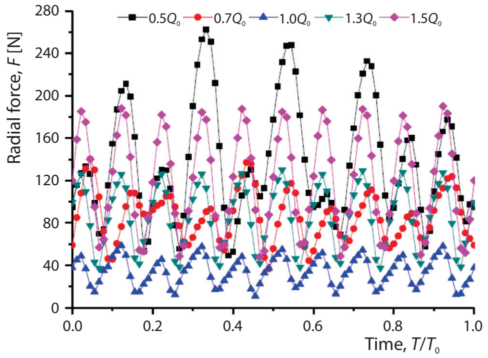

Figure 5. Response of inlet and outlet cooling water temperature and temperature difference of electric reactor with time

The response of inlet and outlet cooling water temperature and temperature difference of electric reactor with time is shown in fig. 5. The simulation and experiment results of inlet and outlet cooling water temperature and temperature difference of fuel cell reactor show the same trend, and the relative error is within 5%.

Control strategy

When the reactor temperature is set at 353 K, and the membrane humidity is 100%, the dynamic response of the reactor current and voltage of 35 kW PEMFC overtime changes, as shown in fig. 6. When the current reactor step changes, overshoot and undershoot occur to the reactor voltage. When the thermal management system controls the reactor temperature, the film humidity is 100% (without considering the film humidity change on the reactor output voltage). The inlet cooling water temperature of the reactor is 75 °C, and the cooling water temperature difference is 5 °C. Three control strategies are simulated. Under different control strategies, the relationship between cooling water flow and radiator fan flow over time is compared, as shown in fig. 7. The water pump can quickly and stably adjust the cooling water flow to a reasonable value, and the response speed and accuracy of cooling water flow to reactor heat production are almost the same [9]. However, radiator fan flow regulation time, response speed, and accuracy vary greatly, and the radiator fan's power consumption is also different.

Flow following current control strategy

The change of inlet and outlet cooling water temperature and temperature difference of fuel cell reactor over time is shown in fig. 8. In the starting stage of the electric reactor, the

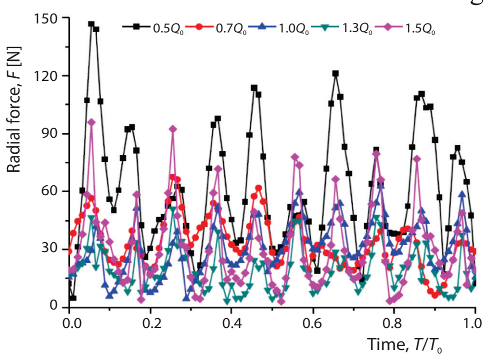

Figure 6. Polarization curve and power curve of fuel cell

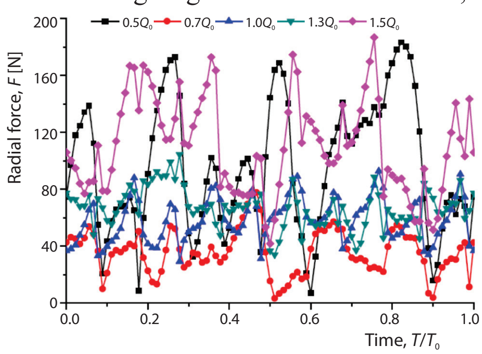

Figure 7. Dynamic response of reactor current and voltage over time

cooling water temperature rises rapidly. In the stable stage of cooling water temperature, the over harmonic oscillation phenomenon exists in the electric reactor's inlet and outlet cooling water temperature. The fluctuation of cooling water temperature and the temperature difference is pronounced under high power.

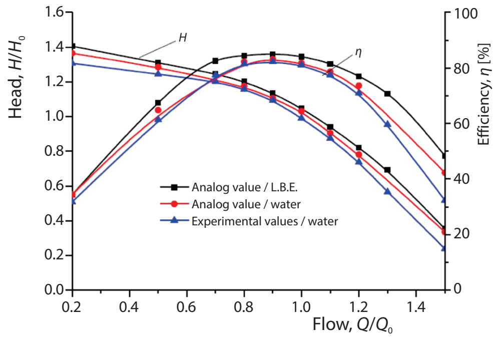

Figure 8. Changes of inlet and outlet cooling water temperature and temperature difference of fuel cell reactor over time

Neural network AdRC control strategy

The inlet and outlet cooling water temperature and temperature difference of fuel cell reactor vary significantly with time. The stable stage of cooling water temperature, the electric reactor's inlet and outlet cooling water temperature still have an over harmonic oscillation phenomenon, and the changing trend is gentle. Moreover, under high power, the fluctuation degree of cooling water temperature is obviously reduced, but the cooling water temperature difference curve's oscillation is intensified.

Flow follows current and power control strategy simultaneously

Import and export of fuel cell stack cooling water temperature and the change of temperature with time are apparent. In the cooling water temperature stable phase, pile import and the export trend is more gentle, cooling water temperature changes under the maximum power is relatively weak overshoot and oscillation phenomenon, its fluctuation significantly weakened, and the cooling water temperature curve of the oscillation is also weakened obviously.

Comparison of control strategies

By comparing the three control strategies' simulation results, we found that the inlet and outlet cooling water temperature and temperature difference of the fuel cell reactor vary significantly with time. From 300-1600 seconds, the cooling water temperature is in the sound stage, and the inlet and outlet cooling water temperature of the electric reactor changes in the same trend, which indicates that the coupling effect between the pump and the radiator fan still exists. When the cooling water flow follows the current and power control strategy at the same time, the changing trend of inlet and outlet cooling water temperature and cooling water temperature difference of the power reactor is the most gentle and close to the control target value, and the oscillation phenomenon is weak at the maximum power [10]. The relative error value between the simulation data and the control target of the inlet and outlet cooling water temperature and temperature difference of the fuel cell reactor represents the fluctuation of the inlet and outlet cooling water temperature and temperature difference of the electric reactor. As shown in fig. 9, the smaller the fluctuation degree range is, the better the control effect of the control strategy is. When the fluctuation degree is 0, the control effect is optimal. Under the control strategy of flow following current and power at the same time, the fluctuation degree of inlet and

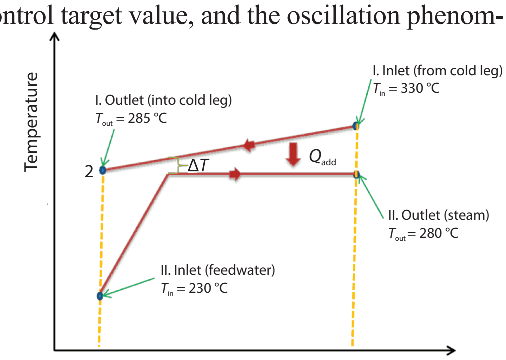

Figure 9. Temperature and temperature difference fluctuation degree of inlet and outlet cooling water of the electric reactor

outlet cooling water temperature of the electric reactor ranges from –1.8% to 2.5%, and the range of temperature difference fluctuation degree is the smallest, which also indicates that the regulating time of cooling water and radiator fan flow is shorter, the response speed is faster, and the accuracy is higher. For these three control strategies, when the reactor changes in a step, the cooling water temperature, and temperature difference have an overshoot phenomenon, and the oscillation phenomenon is easy to occur at the maximum power. The continuous fluctuation of cooling water and radiator fan flow is the main reason for the temperature oscillation phenomenon.

Conclusion

Because of the deficiency of flow following the current control strategy, this paper proposes a flow following current and power control strategy and a neural network active disturbance rejection control method. The simulation research was carried out based on the 35 kW fuel cell reactor model, thermal management system, and its control model. Traffic and follow the study found that current and power control strategy with better control effect and can effectively weaken the coupling effect of the water pump and radiator fan, significantly reduce the pile import and export amount of cooling water temperature and temperature difference of overshoot and adjustment time, the large load, lightening, and maximum power condition can efficiently maintain the fast, stable electricity within the normal operating temperature, to avoid the short term high temperature influence on the operational performance and life of PEMFC. The neural network AdRC control strategy has a poor control effect under the condition of maximum power. The temperature fluctuation degree of inlet and outlet cooling water of the reactor affects the stability of the reactor's output voltage, but the overall control effect is better than the flow following the current control strategy.

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Paper submitted: November 16, 2020
Paper revised: December 30, 2020
Paper accepted: January 18, 2021