Real-time thermal management of open-cathode PEMFC system based on maximum efficiency control strategy

Liangzhen Yin | Qi Li | Tianhong Wang | Lu Liu | Weirong Chen

School of Electrical Engineering, Southwest Jiaotong University, Chengdu, China

Correspondence
Qi Li, School of Electrical Engineering, Southwest Jiaotong University, Chengdu 610031, China.
Email: liqi0800@163.com

Funding information
NEEC Open-end Fund of China, Grant/Award Number: NEEC-2017-B01;
National Key Research and Development Program of China, Grant/Award Number: 2017YFB1201003-019; Application Foundation Project of Science and Technology Plan of Sichuan Province, Grant/Award Number: 19YYJC0698

Abstract
Improving the efficiency of the proton exchange membrane fuel cell (PEMFC) system is the main problem should be solved for the commercialization of PEMFC. In this paper, the efficiency characteristic of PEMFC system under load and stack temperature variation is analyzed through theoretical modeling and experimental verification. For high efficiency operation of PEMFC system, the maximum efficiency control strategy (MECS) is proposed for thermal management of PEMFC system. According to the efficiency characteristics of PEMFC system, the optimal efficiency trajectory of system is obtained under maximum efficiency optimization (MEO). As PEMFC system is a nonlinear system with the characteristics of time-variation, and uncertainty, a constrained generalized predictive control (CGPC) is proposed to realize real-time optimal efficiency trajectory tracking. The MECS based on MEO and CGPC is implemented on-line, experimentally validated on the established H-300 open-cathode PEMFC system. The experimental result shows better tracking ability compared with PID control and testifies the validity of MECS for increasing the system efficiency. Therefore, the proposed MECS can provide better system dynamic response and higher system efficiency.

KEYWORDS
constrained generalized predictive control (CGPC), maximum efficiency control strategy (MECS), maximum efficiency optimization (MEO), Proton exchange membrane fuel cell (PEMFC), thermal management

1 | INTRODUCTION

With the rapid development of science and technology, energy shortage and environmental pollution have attracted widely attention in the last decade. Hence, the development and utilization of clean and renewable energy become the inevitable trend in the world [1,2]. As the renewable energy such as solar and wind have the characteristic of intermittency and uncertainty, it is generally difficult to match the energy production with the energy demand in application [3,4]. Therefore, it is necessary to introduce hydrogen energy as the transit energy to help matching the energy production and energy demand. As an energy storage medium, hydrogen energy cross the fields of electricity, heat and fuel, which can promote the integration of energy supply and improve
the efficiency and stability of renewable energy. The key component of hydrogen energy utilization is the fuel cell. Fuel cell regarded as a novel energy conversion device, which use hydrogen as fuel, can convert the chemical energy form hydrogen directly into electricity with high efficiency and only product heat and water. Among these technologies, proton exchange membrane fuel cell (PEMFC) gains much attention due to the advantage of good dynamic response, non-pollution, high efficiency, and quick start-up, which has been widely used in automotive applications, stationary power station, combined heat and power (CHP) and portable backup system [5–8].

The output performance of PEMFC system such as net power and efficiency are sensitive to the gas flow rate, gas pressure, humidity, temperature, and so on. In [9], the air flow rate on PEMFC system net power characterization is analyzed on Ballard 1.2 kW Nexa power system. Aiming at avoiding oxygen starvation and maximum net power operation, respectively, the air flow control is designed based on constrained explicit model predictive control (MPC). For better thermal management and avoiding temperature fluctuation, through electrochemical reaction mechanism and thermodynamic principle analysis, a control-oriented cooling system model is established which is verified on an experimental Ballard 14.4 kW system [10]. In [11], in order to optimize the output power and avoid overheating under external load change, a PI controller based on optimal OER trajectory is proposed to regulate the air flow rate through cooling fans. In [12], in consideration of air compressor power consumption, the energy management strategy based on power coordinating algorithm is presented to distribute the power demand to the PEMFC system and the battery while maintaining the battery SOC at the same time. In [13], the maximum power point tracking (MPPT) is studied in a Fuel cell and DC-DC converter cascade systems in the conditions of the fuel cell parameter variations and load changes.

Differ from typical PEMFC system, the cathode of the open-cathode PEMFC is designed directly connect with the air. The oxygen for electrochemical reaction is by supplied DC cooling fans. Thus, the coupling degree between air supply subsystem and cooling subsystem is increased [14–16]. The coupling phenomenon existed in air supply subsystem and cooling subsystem will increase the difficulty to analyze the efficiency characteristic of PEMFC system [17]. In [18], the relationship between maximum power and stack temperature is obtained. In [19], a concentrated parameter dynamic model of an open-cathode PEMFC system is proposed to study the system efficiency characteristic. Currently, the control system design for the commercial open-cathode PEMFC system is simple which lead to lower output performance and shorter service life of the system. Hence, many intelligent control strategies have been applied to ensure system PEMFC normal operation. In [20], a 3D fuzzy logic control for temperature management is implemented and verified on a real H-100 fuel cell. In [21], a cascaded control strategy is proposed for thermal management of H-100 open-cathode PEMFC system. The extremum seeking control (ESC) algorithm is used to seek the optimal temperature trajectory, while the cascaded PI controller is applied to track the optimal temperature trajectory provided by ESC. In [22], taking into consideration of unknown dynamics and disturbances of the PEMFC system, an ADRC combined with ESO is proposed to realize PEMFC stack temperature control with guaranteed performance. In [23], a MIMO PEMFC system controller based on fuzzy logic control (FLC) is implemented to regulate the stack temperature and relative humidity real time. At present, the main research on the PEMFC stack is focused on the optimization of output performance of the PEMFC itself, and less attention is focused on the auxiliary power consumption and system efficiency analysis.

In this paper, through thermal and electrochemical modeling, the PEMFC system efficiency characteristic is analyzed, and the maximum efficiency trajectory is obtained by experiments. Considering the system characteristics of nonlinearity, time variation, a maximum efficiency control strategy (MECS) is proposed for thermal management of PEMFC system based on maximum efficiency optimization (MEO) and constraint generalized predictive control (CGPC). Finally, the proposed control strategy is verified on a real H-300 open-cathode PEMFC system.

2 | EXPERIMENTAL OPEN-CATHODE PEMFC SYSTEM

The experimental open-cathode PEMFC system is shown in Figure 1. The PEMFC stack is chosen as a 60 cells, 300 W open-cathode PEMFC stack from Shanghai Horizon Fuel Cell Technologies and effective membrane area of 22.5cm². The PEMFC stack is self-humidified, air-cooled, and the stack cathode is open to the air. Because of the limited experimental conditions, the study in this paper focus on the external characteristics of the open-cathode PEMFC system, and ignoring the effect of internal structure of the stack on the performance of the system. The main auxiliary components of open-cathode PEMFC system are DC cooling fans which are used to provide oxidant air to the cathode of PEMFC stack and remove heat from the stack by forced convection. Hence, the mass flow diagram of cathode and cooling system of the open-cathode PEMFC system is strong coupling which is represented by yellow arrow in Figure 1. A manual pressure regulator is used to maintain hydrogen
pressure of the anode inlet to about 0.60 bar. Solenoid valves are installed at the inlet and outlet of the stack anode to manage the hydrogen intake in the inlet of the stack anode and hydrogen purging in the outlet of the stack anode. The mass flow diagram of anode is represented by blue arrow in Figure 1. The programmable DC electronic load is equipped for the tests of the PEMFC output performance.

During the electrochemical reaction of open-cathode PEMFC system, proper control must be used to manage the operating parameters of the open-cathode PEMFC system. Thus, for normal operation of PEMFC system, a PEMFC system controller must be set up. In order to facilitate the development and experimental verification of complex control algorithms, in this work, the control platform design of the experimental PEMFC system is implemented by LabVIEW software. The data acquisition card (DAQ) is used to transmit data and control signals between LabVIEW software and PEMFC system. The DAQ card in the experiments selects USB-1902 DAQ manufactured by ADLINK Company. The system operation parameters such as stack temperature, voltage and current are collected by the sensor installed at the corresponding position, and then, through the signal processing circuit, the selected signals converted to the 0-10 V voltage signal is sent to DAQ card. Through the USB serial communication, The LabVIEW control system receives the PEMFC operation parameters, and then, the LabVIEW control system generates the control signals according to the received operating parameters and controls the auxiliary equipment such as DC cooling fans, hydrogen valve, and purge valve.

### 2.1 Thermal and electrochemical modeling of open-cathode PEMFC system

The open circuit voltage $V_{oc}$ of the single fuel cell is mainly determined by the operating conditions of the PEMFC stack which can be calculated through the Nernst equation and the principle of the Gibbs free energy change [5,7,19]:

$$\begin{align*}
V_{oc}(t) &= 1.229 - \left(8.5 \times 10^{-4}\right) \times \left(T_{fc}(t) - 298.15\right) \\
&\quad + \frac{RT_{fc}(t)}{2F} \times \left(\ln P_{H2}(t) + \frac{1}{2} \ln P_{O2}(t)\right)
\end{align*}$$

(1)

where, $T_{fc}$ represents the stack temperature (K), $P_{H2}$ is anode hydrogen pressure (Pa), $P_{O2}$ is the cathode oxygen pressure (Pa), $F$ is Faraday’s constant (C/mol), $R$ is the universal gas constant (J/(mol. K)).

While the PEMFC stack is in operation, a series of chemical and physical reactions will occur on the stack electrode, and every process have some resistance. Therefore, in order to keep operation of the electrochemical reaction, some energy must be consumed to overcome the resistances. However, when overcome the resistances, the electrode potential deviation phenomenon is observed, this phenomenon is called polarization of PEMFC stack. According to the difference of the action mechanism, the polarization of PEMFC stack can be divided into activation polarization, ohmic polarization and concentration polarization. Thus, voltage loss caused by the polarization includes activation overvoltage ($V_{act}$), ohmic overvoltage ($V_{ohm}$) and concentration overvoltage ($V_{con}$). Based on the empirical formula of the PEMFC stack output characteristic, the actual single cell output...
The output voltage of the PEMFC stack can be expressed as [5,7,19]:

\[ V_{\text{cell}}(t) = V_{\text{oc}}(t) - V_{\text{act}}(t) - V_{\text{ohm}}(t) - V_{\text{con}}(t) \]  

(2)

and:

\[
\begin{align*}
V_{\text{act}}(t) &= a_1 + \frac{\Delta s}{2F}(T_{\text{fc}}(t) - T_0) + (h_2 T_{\text{fc}}(t) + h_3 T_{\text{fc}}(t) + h_4) \left( 1 - e^{-h_5 I_{\text{fc}}(t)} \right) \\
V_{\text{ohm}}(t) &= R_{\text{ohm}} I_{\text{fc}}(t) = (h_6 + h_7 T_{\text{fc}}(t)) I_{\text{fc}}(t) \\
V_{\text{con}}(t) &= i_c(t) (h_8 I_{\text{fc}}(t))^n
\end{align*}
\]  

(3)

where, \( \Delta s \) is the entropy change of the reaction (J/(mol. K)), and \( [h_1, h_2, h_3, h_4, h_5, h_6, h_7, h_8] \) are the constant coefficients should be identified empirically.

Generally, the PEMFC stack is composed of with the \( N_{\text{cell}} \) same single cell which is connected in series. Thus, the output voltage of the stack \( V_{\text{fc}} \) is:

\[ V_{\text{fc}}(t) = N_{\text{cell}} V_{\text{cell}}(t) \]  

(4)

The output power of the PEMFC stack \( P_{\text{fc}} \) can be calculated as:

\[ P_{\text{fc}}(t) = V_{\text{fc}}(t) I_{\text{fc}}(t) \]  

(5)

The efficiency of PEMFC stack \( \eta_{\text{HHV}} \) is defined as a ratio of the power of the stack \( P_{\text{fc}} \) and the power of hydrogen consumed \( P_{\text{fuel}} \) [24]:

\[ \eta_{\text{HHV}}(t) = \frac{P_{\text{fc}}(t)}{P_{\text{fuel}}(t)} = \frac{V_{\text{fc}}(t) I_{\text{fc}}(t)}{2F} = \frac{V_{\text{fc}}(t)}{1.482 N_{\text{cell}}} \]  

(6)

where, \( \Delta H_{\text{HHV}} \) is the higher heating value of hydrogen (kJ/mol). From Equation 6, it can be observed that the efficiency of the stack \( \eta_{\text{HHV}} \) is mainly determined by \( V_{\text{fc}} \), which in turn is associated with \( I_{\text{fc}} \) through the polarization curve. In this work, the open-cathode PEMFC stack is selected as the research object. The main auxiliary component of the system is the cooling fans, the power consumption \( P_{\text{aux}} \) caused by the operation of the system which will diminish the system efficiency \( \eta_{\text{fc}} \). Therefore, while calculating the system efficiency \( \eta_{\text{fc}} \), the parasitic power consumed by auxiliary components should be concerned [24]:

\[ \eta_{\text{fc}}(t) = \eta_{\text{HHV}}(t) \frac{P_{\text{net}}(t)}{P_{\text{fc}}(t)} = \eta_{\text{HHV}}(t) \frac{P_{\text{fc}}(t) - P_{\text{aux}}(t)}{P_{\text{fc}}(t)} = \frac{V_{\text{fc}}(t)}{1.482 N_{\text{cell}}} \left( 1 - \frac{P_{\text{aux}}(t)}{V_{\text{fc}}(t) I_{\text{fc}}(t)} \right) \]  

(7)

Where, \( P_{\text{net}}, P_{\text{aux}} \) represents the net power and parasitic power of PEMFC system, respectively. According to the Equation 7, after the information of \( V_{\text{fc}}, P_{\text{aux}}, I_{\text{fc}} \) are obtained by the sensor installed at the corresponding position, the system efficiency \( \eta_{\text{fc}} \) can be calculated.

For steady-state polarization characteristic test of H-300 PEMFC stack, \( P_{\text{O}_2} \) is adjusted to 0.60 bar through pressure regulator. The tested polarization curve of H-300 PEMFC stack under different stack temperature is shown in Figure 2. According to the manual of H-300 stack provided by the Horizon Company, the maximum stack temperature is 70°C. In this paper, the polarization curve of H-300 PEMFC stack under different stack temperature is obtained by practical system operation instead of test platform of fuel cell system. The increase of the stack temperature mainly depend on the heat generated by the electrochemical reactions of the stack while in system operation. On the one hand, when the output power of the PEMFC system is low, the stack temperature cannot reach a higher value even if the cooling fan maintains a minimum speed to provide sufficient air for the electrochemical reaction. Therefore, in the test of the polarization curve of H-300 PEMFC stack under different stack temperature will be constrained by the operating characteristics of the system. On the other hand, excessive \( T_{\text{fc}} \) will lead to an obvious irreversible decline in \( V_{\text{fc}} \), and ultimately lead to downward trend in the system efficiency will be discussed in section 2.2. Therefore, the temperature should not be too high for the polarization curve test of open-cathode PEMFC system in the full operating range. When \( I_{\text{load}} \) increases, \( V_{\text{fc}} \) gradually declines and

![FIGURE 2 polarization curve of H-300 PEMFC stack under different stack temperature](Color figure can be viewed at wileyonlinelibrary.com)
$P_{fc}$ rises. But for $η_{fcs}$, in the area where $I_{load}$ is small, $η_{fcs}$ increases with the increase of $I_{load}$. After $η_{fcs}$ reaches its maximum efficiency point, it can be observed that $η_{fcs}$ will decrease with the increase of $I_{load}$ as shown in Figure 2. The maximum efficiency point of system obtained at $I_{load}$ equals to3A. For high efficiency operation of the system, in the process of system operation, the system should be operated at high efficiency region which is 3A-8A according to the efficiency curve of PEMFC system. Meanwhile, according to the operating behavior of the open-cathode PEMFC system, whether operating the open-cathode PEMFC system at lower output current range (activation polarization region) or higher output current range (concentration polarization region) is not conducive to efficient, safe and stable operation of the system. In Figure 2, it can be observed that when the load current is low, the effect of $T_{fc}$ on system output performance such as voltage and efficiency is very small, and with the increase of the load current $I_{load}$, $T_{fc}$ becomes an important parameter affecting output performance of system. Before conducting the polarization characteristic curve tests of H-300 stack, the PEMFC system runs under rated power for long time to achieve stable output performance.

From Equation (1-7), the PEMFC system efficiency is mainly related operating conditions stack temperature $T_{fc}$, stack output current $I_{fc}$, and system parasitic power $P_{aux}$. In the open-cathode PEMFC system, $P_{aux}$ can be regarded as the power consumed by the cooling fans $P_{fans}$. For the purpose of seeking the relationship between the cooling fans $P_{fans}$ and stack operating conditions, the thermal model of PEMFC system needs to be studied and built. According to the energy balance criterion, the Thermodynamic behaviour inside the stack can be described as follows:

$$Q_{fc}(t) = Q_{tot}(t) - Q_{ele}(t) - Q_{cool}(t) \tag{8}$$

where, $Q_{tot}$ represents the total power generated by the electrochemical reactions inside the stack, $Q_{ele}$ represents the electrical power generated by the stack, and $Q_{cool}$ represents the heat loss by cooling from forced convection. According to the corresponding physical process, the above energy in unit time can be expressed as [6]:

\[
\begin{align*}
Q_{fc}(t) & = C_{fc} \frac{dT_{fc}(t)}{dt} \\
Q_{tot}(t) & = \frac{N_{cell}I_{fc}(t)}{2F} \Delta H \\
Q_{ele}(t) & = V_{fc}(t)I_{fc}(t) \\
Q_{cool}(t) & = \eta_{fan} C_{air} m_{air}(t)(T_{fc} - T_0)
\end{align*}
\tag{9}
\]

where $C_{fc}$ is the thermal capacitance of the PEMFC stack (J/K), $\Delta H$ represents the enthalpy change of hydrogen (J/mol), $\eta_{fan}$ is the efficiency of cooling fans, $C_{air}$ represents the specific heat coefficient of air, $m_{air}$ represents the air mass flow rate provided by cooling fans (kg/s), $T_0$ is the ambient temperature (K). From Equation (8-9), $m_{air}$ represents the function of operating conditions $T_{fc}$, $I_{fc}$ and $V_{fc}$. According to the user manual of the cooling fans, $m_{air}$ is mainly related to the power consumed by the DC cooling fans $P_{fans}$:

$$P_{fans}(t) = g(m_{air}(t)) = g'(V_{fc}(t), T_{fc}(t), I_{fc}(t)) \tag{10}$$

### 2.2 Efficiency characteristic analysis of the PEMFC system

In this work, the open-cathode PEMFC stack is selected as the research object. The cathode of the H-300 stack is designed directly connected with the air. The main auxiliary component of the system is the cooling fans, which remove heat generated by the electrochemical reaction inside the stack and provide oxygen to the stack cathode for electrochemical reaction. Hence, the air supply and cooling of the open-cathode PEMFC system is strong coupling, which will increase the difficulty of controller design of open-cathode PEMFC system. The cooling fans operation implies a power consumption that diminishes the system efficiency. On the one hand, the lower cooling fans speed may cause oxygen starvation of the system and over-heat of the stack, which cause output performance decrease. On the other hand, the higher cooling fans speed may cause lower stack temperature increase the parasitic power of the system. Meanwhile, the open-cathode PEMFC system adopts self-humidification technology to get rid of complex external humidifying circuit. Thus, the water management of open-cathode PEMFC system is mainly implemented by evaporation by thermal management and purging mode in the stack anode. Experiments show that water management of purging mode in the stack anode cannot meet the needs of the open-cathode PEMFC system. Thus, the water management of open-cathode PEMFC system is mainly determined by thermal management of the system. If the stack temperature of the open-cathode PEMFC system is low, the amount of water taken away by the cooling system through evaporation is less than that generated by the electrochemical reaction inside the stack. The generated water accumulates at the anode of the stack, which results in flooding and deteriorates the output performance of the open-cathode system. If the stack temperature of open-cathode PEMFC system is high, the amount of water taken away by the cooling system through evaporation is more than that generated by the electrochemical reaction inside the stack which will result in membrane drying. Through the above analysis, the
thermal management of open-cathode PEMFC system will affect the air flow management and water management of open-cathode of PEMFC system. In the purpose of maximum efficiency operation of open-cathode PEMFC system, the effect of thermal management on the system efficiency characteristic should be fully understood.

From thermal and electrochemical modelling of PEMFC system, $V_{fc}$ is mainly related to the operating conditions $T_{fc}$, $I_{fc}$, $P_{H2}$ and $P_{O2}$. Furthermore, the cathode structure of open-cathode PEMFC stack is directly connected with air, the air partial pressure of stack can be approximately regarded as a constant value which equals to the atmospheric pressure. The constant pressure control is adopted to the hydrogen inlet of the stack. Thus, in the operation of open-cathode PEMFC system, the $P_{H2}$ and $P_{O2}$ can be regarded as a constant value, the stack output voltage can be expressed as:

$$V_{fc}(t) = f(T_{fc}(t), I_{fc}(t))$$  \hspace{1cm} (11)

According to definition of system efficiency $\eta_{fcs}$, parasitic power consumption $P_{aux}$, stack output voltage $V_{fc}$ shown in Equation 7, Equation 10, Equation 11, respectively, $\eta_{fcs}$ is related to $I_{fc}$, $T_{fc}$, which can also be qualitatively expressed as a function of $I_{fc}$, $T_{fc}$:

$$\eta_{fcs}(t) = h(I_{fc}(t), T_{fc}(t))$$  \hspace{1cm} (12)

Therefore, under the constant load current, the stack temperature will be the key factor to the system efficiency. To further understand system efficiency characteristic, experiments carried out on the established open-cathode PEMFC system which is shown in Figure 3. In the operation of the open-cathode system, the DC cooling fans need to maintain the minimum speed to provide oxygen for the electrochemical reactions inside the stack. When load current of the PEMFC system is relatively small, and the heat generated by the system is less. Although the speed of the DC cooling fans have been reduced to its minimum, the heat dissipated by the DC cooling fans and the heat generated by the PEMFC stack have reached a balance state, which makes it difficult to raise the temperature of the PEMFC system. Therefore, when the PEMFC system starts up at a small load current, for the purpose of rapidly increasing the temperature of the PEMFC system, the fan control voltage of the PEMFC system should be set to its minimum, and the load current should be gradually increased after the temperature rises. The higher the load current of the open-cathode PEMFC system, the faster the temperature of the PEMFC system will rise. Therefore, the experiment of temperature on the system efficiency characteristics needs to be carried out under the condition of high load current. After the load current is stabilized at the rated current of 8A, the efficiency characteristic test is carried out. The dynamic experiments carried out for system efficiency characteristic are as follows:

**Step 1:** Start the experimental open-cathode PEMFC system at low current and gradually increase the load current;

**Step 2:** Keep the open-cathode PEMFC system in stable operation at its rated output current 8A for a period of time to fully activate its performance;

**Step 3:** Adjust the cooling fans control signal in temperature closed loop to regulate the stack temperature at a pre-set points;

![FIGURE 3](image-url) experimental platform of open-cathode PEMFC system [Color figure can be viewed at wileyonlinelibrary.com]
Step 4: Increase the set point of the stack temperature and then repeat Step 3 until the decline in efficiency was observed;

Step 5: Record and save the real-time operation parameters through NI DAQ card which can monitor the current state of the PEMFC system such as $T_{fc}$, $V_{fc}$, $I_{fc}$, $P_{aux}$, $P_{net}$.

Step 6: Decrease the output current of the PEMFC system and then jump to Step 3–5 until the output current equals to 3A according to the operating region of the open-cathode of the PEMFC system.

Figure 4 shows the dynamic performance of PEMFC system with the changing stack temperature condition under load current at 7A. When increasing $T_{fc}$, it can be clearly observed that $V_{fc}$ has a significant rise, but with the increase of $T_{fc}$, the growth rate of $V_{fc}$ decreases. When $T_{fc}$ reaches optimal value, and then $V_{fc}$ will decline rapidly as $T_{fc}$ continues to rise. However, $P_{aux}$ continues to decrease with $T_{fc}$. As can be seen in Figure 4, when $T_{fc}$ is over 51°C, even though $T_{fc}$ is well stabilized near the set value, $V_{fc}$ decays obviously and the rate of voltage decay trends to rise rapidly with the increase of the set point of $T_{fc}$. Therefore, for long term operation of PEMFC system, it is vital to avoid the stack operating at the fast decay region of the system output performance.

According to the collected real-time operation parameters of PEMFC system $T_{fc}$, $V_{fc}$, $I_{fc}$, $P_{aux}$ and efficiency calculation equation, the system efficiency can be obtained.

The effect of $T_{fc}$ on $\eta_{fcs}$ under load current at 7A is shown in Figure 5. As seen in Figure 5(a), maximum efficiency point appears at $T_{fc} = 56^\circ$C. When the system is operating at $44^\circ$C–$56^\circ$C, it can be observed that $\eta_{fcs}$ can be increased 3% by regulating the temperature setting point from $44^\circ$C to $56^\circ$C. The dynamic characteristics of system efficiency in this operating area are shown in Figure 5(b). As long as $T_{fc}$ is stable near the temperature setting point, the efficiency of PEMFC system will maintain near a stable value. Therefore, the left area of the maximum efficiency point is suitable for long-term operation of the system. When $T_{fc}$ exceeds the maximum efficiency point $T_{fc} = 56^\circ$C, although the increase of $T_{fc}$ is conducive to reducing parasitic power consumption of PEMFC system, excessive $T_{fc}$ will lead to an obvious irreversible decline in $V_{fc}$, and ultimately lead to downward trend in the system efficiency which is shown in Figure 5(c). A nearly 0.15% per minute system efficiency decrease is observed in Figure 5(c). Therefore, too high or too low $T_{fc}$ is not conducive to the efficient operation of PEMFC system. In order to improve $\eta_{fcs}$, $T_{fc}$ must be stabilized near the maximum efficiency point through proper thermal management.

3 | MAXIMUM EFFICIENCY CONTROL STRATEGY OF OPEN-CATHODE PEMFC SYSTEM

In order to improve system efficiency, furthermore, considering the inherent complexity of PEMFC system, the maximum efficiency control strategy (MECS) based on maximum efficiency optimization (MEO) and constraint generalized predictive control (CGPC) is proposed. The structure of the proposed MECS is shown in Figure 6. In the design of MECS, the load current $I_{load}$ is considered as a measurable but uncontrollable external disturbance variable. According to the real-time collected load current of open-cathode PEMFC system, the control system obtains the optimal temperature under the optimal efficiency trajectory under MEO which is discussed in section 3.1. CGPC is a typical feedback control method which is widely used in industrial production due to its capability of obtaining a satisfied control for system with the characteristics of nonlinearity, time-variation. Aiming at the disadvantage of the minimum variance based self-tuning control which requires high precision of the model, CGPC algorithms adopts rolling optimization strategy, which possess the advantage of both adaptive control and predictive control. CGPC algorithm has low requirement for model and strong fault tolerance and robustness. In this paper, as PEMFC system is a nonlinear system with the characteristics of time-
variation, and uncertainty, CGPC is proposed for thermal management of open-cathode PEMFC system to realize real-time optimal efficiency trajectory tracking. The optimal temperature $T_{\text{ref}}$ and the real-time collected stack temperature $T_{fc}$ are sent into the reference trajectory for output softening process discussed in section 3.3.1. After the difference between optimal temperature reference trajectory and output predicted temperature obtained by output predicting module detailed in section 3.3.2, the optimal unconstrained control sequence is obtained by rolling optimization in the finite time domain. Further consideration that the constraint are existed in the system control input caused by the actuator actual physical input limitations and system requirements show in section 3.3.3. Therefore, the input constraints should be concerned in DC cooling Fans optimal control voltage solution. Considering the uncertainty and the slow time-varying characteristics of open-cathode PEMFC system, meanwhile, in the purpose of avoiding the influence of model mismatch on the control accuracy, the forgetting factor recursive least square (FFRLS) algorithm detailed in section 3.2 is used for online identification and correction of model parameters in each control cycle.

### 3.1 Maximum efficiency optimization of PEMFC system

As seen in Figure 5(a), the maximum efficiency characteristic is existed in thermal management of PEMFC system. Therefore, a maximum efficiency optimization (MEO) is needed to obtain the optimal efficiency trajectory of PEMFC system. While the system is operating under MEO, only in this way can we realize the maximum efficiency operation the practical application of open-cathode PEMFC system. The effects of $T_{fc}$ on $\eta_{fcs}$ in high efficiency region ($3A \leq I_{\text{load}} \leq 8A$) are shown in Figure 7. The maximum efficiency points under different load current conditions can be obtained by processing the experimental data shown in Figure 7. With the increasing of $I_{\text{load}}$, the maximum efficiency point is decreased according to polarization characteristic of the PEMFC system, while the corresponding system parameter stack temperature of maximum efficiency point gradually increases from $49^\circ C$ to $58^\circ C$. Through the calculated efficiency curves of the system, the optimal efficiency trajectory is obtained through piecewise polynomial fitting method based on QR decomposition which is represented by green dotted line in Figure 7.
3.2 Control-oriented modeling of open-cathode PEMFC system based on on-line identification method

The thermal management of open-cathode PEMFC system is implemented by real-time adjusting the fan speed of DC cooling fans. In order to facilitate model identification and control system design for the system, the dynamic model of PEMFC system thermal management should be fully understood and modeled. As the mechanism modeling of PEMFC system is too complex to meet the real-time control requirements, in this paper, a modeling method based on system identification is adopted for control-oriented modeling of PEMFC system. According to the ways of implementation, system identification can be divided into on-line and off-line system identification. Although off-line identification can shorten the calculation time, the aging of the system and the change of the external environment will cause the change of system characteristics, which makes it difficult for the system model obtained by off-line identification to accurately represent the nonlinear characteristics of the open-cathode PEMFC system, and the precision of the off-line identification is poor which cannot satisfy the requirement of model-based controller development. Through thermal and electrochemical modeling of the system in section 2.1, it can be concluded that PEMFC system is a complex nonlinear parameter time-varying system. Thus, the off-line linear predictive model have no promising precision to predict the stack temperature variation in the future. However, the stack temperature tracking ability of CGPC is closely related to the prediction precision. In this paper, in the purpose of improving the tracking ability of CGPC, in each control cycle, a local approximate linearization method is adopted to transform the complex PEMFC model into a linear control-oriented controlled auto regressive moving average (CARMA) model:

\[ A(z^{-1})y(k) = B(z^{-1})u(k - d) + v(k) \]  

where \( y \) is output variable of the system, in this paper, \( y = T_{fc} \); \( u \) represents input variable of the system, in this paper \( u = u_{fa} \), \( v \) is the estimation error vector caused by higher-order dynamics and disturbances of the system, \( z^{-1} \) represents the back shift operator of the system, \( d \) represents the time delay of the system, and \( k \) is the discrete sampling time of the system. \( A(z^{-1}), B(z^{-1}) \) are defined as follows:

\[
\begin{align*}
A(z^{-1}) &= 1 + a_1 z^{-1} + ... + a_{na} z^{-na} \\
B(z^{-1}) &= b_0 + b_1 z^{-1} + ... + b_{nb} z^{-nb}
\end{align*}
\]

The CARMA model expressed by difference equation can be expanded as:

\[ y(k) = \varphi^T(k)\theta(k) + v(k) \]

where, \( \varphi(k) \) is the input data vector of the system, and \( \theta(k) \) is the model identification parameter:

\[
\varphi(k) = \begin{bmatrix}
-y(k-1) \\
\vdots \\
-u(k-d)
\end{bmatrix}, \theta(k) = \begin{bmatrix}
a_1 \\
\vdots \\
b_{nb}
\end{bmatrix}
\]

The on-line identification method based on forgetting factor recursive least square (FFRLS) algorithm is used to identify the parameters of the control-oriented CARMA model for the nonlinear PEMFC system for its simple operation, and Strong identification ability against with uncertainty of system parameters. In the on-line modeling process, the output current and ambient temperature and humidity conditions of PEMFC system are treated as unpredictable disturbances, and the model parameters are corrected online in each control cycle to eliminate the influence of external disturbances on the system dynamic model. And then, the on-line identification model is used as a prediction model to describe the nonlinear control object \([25,26]\):

\[
\begin{align*}
\dot{\theta}(k) &= \dot{\theta}(k - 1) + K(k) \left[ y(k) - \varphi^T(k)\dot{\theta}(k - 1) \right] \\
K(k) &= \frac{P(k - 1)\varphi(k)}{\mu + \varphi^T(k)P(k - 1)\varphi(k)} \\
P(k) &= \frac{1}{\mu} \left[ I - K(k)\varphi^T(k) \right] P(k - 1)
\end{align*}
\]
Where, kalman gain $K(k)$ represents the correction degree. The bigger the kalman gain $K(k)$, the better the correction of system parameters, and $\mu$ ($0 < \mu < 1$) represents the forgetting factor.

### 3.3 Constraint generalized predictive control design

CGPC has been widely used in industrial production due to its ability of obtaining a satisfied control results for system with the characteristics of nonlinearity, time-variation. CGPC has low requirement for model and strong fault tolerance and robustness. It mainly includes the following important steps: 1) output predicting, 2) rolling optimization strategy, 3) input constraints, 4) reference trajectory.

#### 3.3.1 Output Predicting

The CGPC makes use of the control-oriented CARMA model obtained by FFRLS algorithm to predict the stack temperature variation in the future time $k + N$. According to the history I/O data of the PEMFC system. The best prediction of the stack temperature is given by Equation (18) and Diophantine equation in the vector form is as follows [27]:

$$Y^* = Y_m + G\Delta U \quad (17)$$

and,

$$Y^* = \begin{bmatrix} y^*(k + d | k) \\
y^*(k + d + 1 | k) \\
\vdots \\
y^*(k + N | k) \end{bmatrix}; \quad Y_m = \begin{bmatrix} y_m(k + d) \\
y_m(k + d + 1) \\
\vdots \\
y_m(k + N) \end{bmatrix}$$

$$\Delta U = \begin{bmatrix} \Delta u(k) \\
\Delta u(k + 1) \\
\vdots \\
\Delta u(k + N - d) \end{bmatrix} \quad (18).$$

where, $Y^*$ is the minimum variance prediction output vector ($d \leq j \leq N$); $Y_m$ is the predicted output vector ($d \leq j \leq N$) based on the historical input and output data before time $k$; $\Delta U$ is the future input increment vector; $N$ represents the predicted length of CGPC.

The control matrix $G$ can be expressed as follows:

$$G = \begin{bmatrix} g_{1,0} & 0 & \cdots & 0 \\
g_{2,0} & g_{1,0} & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots \\
g_{N-d+1,0} & g_{N-d,0} & \cdots & g_{1,0} \end{bmatrix}_{(N-d+1) \times (N-d+1)} \quad (19)$$

The output prediction of the system $y_m(k + j)$ is solved:

$$\begin{cases} y_m(k + j) = y(k + j), j \leq 0 \\
y_m(k + j) = -\sum_{i=1}^{na} a_i y_m(k + j - i) + \sum_{i=0}^{na} b_{1,i}\Delta u \\
(k + j - d - i | k), j = 1, 2, \ldots, N. \quad (20)\end{cases}$$

where:

$$\Delta u(k + j | k) = \begin{cases} 0, j \geq 0 \\
\Delta u(k + i), j < 0 \end{cases}$$

$$\Delta u(k + i) = u(k + i) - u(k - 1), i = 0, 1, \ldots, N - d$$

The elements in the control matrix $G$ can be recursively recurred by the follow equation:

$$g_{j,0} = g_{1,j-1} - \sum_{i=1}^{j-1} a_i b_{j-i,0}, j = 2, 3, \ldots, N - d + 1 \quad (21)$$

where the $b_{k,0}$ is identification value of system parameter $b_0$ at time $k$; $j_i = \min\{j, na\}$; Specially, when $j > nb$, $g_{1,j+1} = 0$.

#### 3.3.2 Rolling Optimization Strategy

When solving the current optimal control voltage of DC cooling fans, the rolling optimization strategy in finite time-domain is adopted instead of the invariable global optimization strategy. Meanwhile, the optimization process is implemented on-line based on the latest information of system I/O data which in need can correct the uncertainty caused by model mismatch in time, and has better robustness. In the design of CGPC, increment sequence of the optimal DC cooling fans control actions which makes $T_{ic}$ track the optimal efficiency trajectory provided by MEO with better dynamic response can be obtained under quadratic cost function defined as follows [24]:

$$J = E\left\{ (Y - Y_r)^T (Y - Y_r) + \Delta U^T \lambda \Delta U \right\} \quad (22)$$

By minimizing the quadratic cost function given in Equation (22), the unconstrained control incremental sequence can be obtained:

$$\Delta U = (G^T G + \lambda I)^{-1} G^T (Y_r - Y_m) \quad (23)$$

where $\lambda$ represents the control weighting coefficient which is used to limit the magnitude of control change. Finally, the current optimal control actions $u(k)$ achieving optimal efficiency trajectory tracking can be obtained:
\[ u(k) = u(k - 1) + \Delta u(k) \]
\[ = u(k - 1) + [1, 0, \ldots, 0] \Delta U \] (24)

### 3.3.3 | Input Constraints

The constraints are often presented in real physical systems due to the actuator limitations and system requirements. When CGPC is applied to the thermal management of open-cathode PEMFC system, the control variable of the system is DC cooling fans voltage \( u_{\text{fan}} \) which is limited to 0-12 V by the physical characteristic. However, in the operation of PEMFC system, the DC cooling fans are not only used to adjust the stack temperature, but also provide the oxygen for the electrochemical reaction inside the stack. Lower oxygen flow is more likely to cause oxygen starvation which will lead to the PEMFC system performance degradation and shorten the service life of the system. Due to the open-cathode structure of the stack and special oxygen supply mode, the air gas flow rate into the cathode is very difficult to measure. For small and medium-sized open-cathode PEMFC stack, the oxygen flow required to maintain the electrochemical reactions inside the stack is extremely low which is not enough to meet the requirements of the thermal management which will lead to overheat of the stack. Therefore, in this paper, the research on maximum efficiency optimization of open-cathode PEMFC system is focused on the thermal management design, and meanwhile, a minimum fan speed is set to avoid the damage of membrane electrodes caused by long-term oxygen starvation. In this paper, according to the large number of experimental results, the input constraints are chosen as: \( u_{\text{min}} = 4 \text{ V}, u_{\text{max}} = 12 \text{ V} \).

### 3.3.4 | Reference Trajectory

In the design of CGPC, the smoothing factor \( \alpha \) is introduced in order to make the system output \( y(k) \) transit to the system set value \( w(k) \) smoothly. Reference trajectory is designed as a first-order smooth model:

\[ \begin{align*}
   y_r(k) &= y(k) \\
   y_r(k + j) &= \alpha \cdot y(k) + (1 - \alpha) \cdot w(k + j)
\end{align*} \] (25)

where, \( w(k) \) \( y(k) \) are the set point and measured values of the stack temperature at time \( k \). When the value \( \alpha \) is so small, the reference trajectory \( y_r(k + j) \) can quickly track the set point \( w(k + j) \), but it will reduce the ability of the system to resist the disturbance in the operation of the system. In contrast, when the value \( \alpha \) is so big, the reference trajectory \( y_r(k + j) \) approaches the trajectory smoothly, which will sacrifice the dynamic response capability of the system, but enhances the robustness of the system.

In summary, the specific steps of CGPC are as follows:

**Step 1:** Determine the order of PEMFC system: \( na, nb, d \); set the initial values of identification model: \( \Theta(0), P(0), \mu \); set the control parameters of the controller: \( \alpha, N, \lambda \).

**Step 2:** Collect the current output \( y(k) \) and input \( u(k) \) of PEMFC system, and calculate the current reference trajectory output \( Y_r \) according to Equation (25);

**Step 3:** Solve the identification parameter of dynamic control-oriented linear CARMA model of PEMFC system according to Equation (16);

**Step 4:** Solve the control matrix \( G \) according to Equation (19);

**Step 5:** Calculate and construct the predicted output vector \( Y_m \) according to Equation (20);

**Step 6:** Solve the current optimal control input \( u(k) \) according to Equation (24).

**Step 7:** \( k \rightarrow k + 1 \), back to **Step 2** and continue.

### 4 | EXPERIMENTAL RESULTS AND DISCUSSIONS

In this paper, the proposed MECS based on MEO and CGPC is tested on the experimental PEMFC system shown in Figure 3. According to the handbook of H-300 provided by Fuel Cell Technologies, before starting the PEMFC system, maintain the anode hydrogen pressure at 0.6 bar through the pressure regulator. After observing that the H-300 can establish normal open circuit voltage, the system goes into normal operation states. In the normal operation of PEMFC system, set the purge cycle to 10s with purging time of 200 ms using solenoid valve. In PEMFC start-up stage, the hydrogen supply circuit is purged by nitrogen. In the PEMFC shut-down stage, the only auxiliary equipment of the DC cooling fans system is used to consume the remaining hydrogen in the stack until the average single voltage is less than 0.5 V, so as to avoid the damage of the membrane electrode caused by the high voltage of the stack, and then fill hydrogen circuit with the nitrogen to protect the stack.

In this paper, the control-oriented modeling of open-cathode PEMFC system is implemented by on-line identification method. The order of PEMFC system: \( na, nb, d \) are determined through lots of experiments. On the one hand, the increase of the order of PEMFC system will improve the precision of established control-oriented identification model. On the other hand, the increase of
the order of PEMFC system will increase the complexity for CGPC real-time computing. The precision of identification model under system parameters are shown in Figure 8. The established control-oriented identification model with an error of less than 0.1°C can meet the needs of requirements of CGPC which requires less of the model.

The parameters of the CGPC strategy are selected as: $n_a = 2$, $n_b = 1$, $d = 4$, $\mu = 0.98$, $N = 18$, $\lambda = 0.8$, $\alpha = 0.7$, $\theta(0) = 0$, $P(0) = 10^3 I$, through lots of experiments. Dynamic load change experiments are carried out under constant current mode to verify the dynamic response and tracking ability of the control system under variable load condition. The external load current setting from 3A to 9A is shown in Figure 9(a). Experiments are carried out based on CGPC and PID, respectively. The stack temperature dynamic response and the system efficiency response under variable load condition are shown in Figure 9(b), Figure 9(c), respectively. As shown in Figure 9(b), Figure 9(c), both CGPC and PID control can track the optimal efficiency trajectory of PEMFC system and maintain the system efficiency in case of load variation. But CGPC has better dynamic response and tracking ability which is obviously shown in Figure 9(b). For temperature tracking, when the load current changes from 4A - 3A - 5A - 7A - 8A - 6A - 4A, the temperature tracking overshoot under CGPC are basically close to 0. But, under PID control, the maximum deviation of the temperature tracking during load current change is 0.44°C, 0.22°C, 0.40°C, 0.81°C, 1.25°C, 1.64°C, respectively. With the increase of $I_{load}$, the temperature tracking deviation increases, and the deviation in the load decrease conditions is obviously bigger than the deviation in the load increase conditions.

The overshooting of the stack temperature indicates more parasitic power consumption which will worsen the dynamic characteristics of the efficiency response of PEMFC system. As shown in Figure 10, when the PEMFC is operating at the stable area, the system efficiency can maintain at its optimal efficiency point. In 550 s, when the load current is changed from 6A to 4A, there exist a nearly 1.64°C deviation in stack temperature under PID control, which increased the time for the system to reach the steady state about 10s compared with CGPC shown in Figure 9. The better the temperature tracking ability is, the better the system dynamic response is. In order to improve the dynamic response of PEMFC system, many intelligent controls should be applied to thermal management of the system. Furthermore, if the
PEMFC system operates at overheating area for a long time, although the stack temperature remains stable at this time, the output performance of the PEMFC stack will continue to decline as the water and heat balance inside the stack is broken.

In order to verify the robustness of CGPC, the following experiment is designed. First, fix the setting point of the stack temperature at 45°C. After the stack temperature is stable near the set point, change the external load current to observe the stack temperature dynamic response. The robustness of the CGPC is verified under changing external load shown in Figure 11. As shown in Figure 12, with the external load changing from 5A-8A, the proposed CGPC can maintain the stack temperature around 45°C with the tracking error less than 1°C. Hence, regardless of the change of the load current, the proposed CGPC can stabilize the stack temperature near the set point.

In the working condition as shown in Figure 11, operate the PEMFC system in two operation modes: fixed temperature mode (FTM) and Maximum efficiency mode (MEM), respectively. In MEM, the thermal management of PEMFC system is implemented by MECS based on MEO and CGPC. While in FTM, the thermal management of PEMFC system is implemented by fixed temperature control strategy (FTCS) with CGPC. The dynamic response of the system efficiency is shown in Figure 13. It can be clearly observed that through the proposed MECS, the system efficiency can be increased by nearly 1% on average.

5 | CONCLUSION

In this paper, the efficiency characteristic of the PEMFC system is developed by thermal and electrochemical modeling and optimal efficiency trajectory of the PEMFC system is obtained through the experiments. In order to ensure PEMFC system operating at the optimal efficiency trajectory under the load condition variations, MECS based on MEO and CGPC is proposed to maintain the system efficiency near the optimal efficiency point for the thermal management of PEMFC system. The on-line identification method based on FFRLS algorithm are proposed to model and correct such nonlinear and time-varying control objects. The dynamic loading experiments show CGPC possesses satisfying performance in both tracking ability and robustness. With MECS proposed in this paper, a nearly 1% increase of system efficiency on average is observed in the experimental results. The result of this study can be useful for commercialized application of the PEMFC system.

ACKNOWLEDGEMENTS

The authors would like to thank the reviewers for their helpful suggestions. This work was supported by Application Foundation Project of Science and Technology Plan of Sichuan Province (19YYJC0698), National Key Research and Development Program of China (2017YFB1201003-019), NEEC Open-end Fund of China (NEEC-2017-B01).
REFERENCES

1. Q. Li et al., Power management strategy based on adaptive droop control for a fuel cell-battery-supercapacitor hybrid tramway, IEEE Trans Veh Technol., 67 (7) (2018), 5658–5670.

2. N. Bizon, Real-time optimization strategy for fuel cell hybrid power sources with load-following control of the fuel or air flow, Energ. Conver. Manage., 157 (2018), 13–27.

3. H. Yang et al., Hierarchical distributed control for decentralized battery energy storage system based on consensus algorithm with pinning node, Protection Control Mod Power Syst, 3 (2018), 6.

4. G. Magdy et al., Microgrid dynamic security considering high penetration of renewable energy, Protection Control Mod Power Syst, 3 (2018), 23–32.

5. D. Zhou et al., Online energy management strategy of fuel cell hybrid electric vehicles: A fractional-order extremum seeking method, IEEE Trans Ind Electron, 65 (99) (2018), 6787–6799.

6. L. Yin et al., Experimental analysis of optimal performance for a 5 kW PEMFC system, Int. J. Hydrogen Energy, 44 (11) (2019), 5499–5506.

7. M. Piffard et al., Sliding mode observer for proton exchange membrane fuel cell: Automotive application, J. Power Sources, 388 (2018), 71–77.

8. A. Tahri et al., Nonlinear adaptive control of a hybrid fuel cell power system for electric vehicles - a Lyapunov stability based approach, Asian J Control, 18 (1) (2016), 166–177.

9. A. Arce et al., Real-time implementation of a constrained MPC for efficient airflow control in a PEM fuel cell, IEEE Trans Ind Electron, 57 (6) (2010), 1892–1905.

10. X. Zhao et al., Thermal management system modeling of a water-cooled proton exchange membrane fuel cell, Int. J. Hydrogen Energy, 40 (7) (2015), 3048–3056.

11. K. Ou, Y. X. Wang, Y. B. Kim, Performance optimization for open-cathode fuel cell systems with overheating protection and air starvation prevention, Fuel Cells, 17 (3) (2017), 299–307.

12. Q. Ouyang et al., Nonlinear MPC controller design for AIR supply of PEM fuel cell based power systems, Asian J Control, 19 (3) (2017), 929–940.

13. R. Dadkhah Tehrani and F. Shabani, Performance improvement of fuel cells using perturbation-based extremum seeking and model reference adaptive control, Asian J Control, 19 (6) (2017), 2178–2191.

14. Q. Meyer et al., Optimisation of air-cooled, open-cathode fuel cells: Current of lowest resistance and electro-thermal performance mapping[J], J. Power Sources, 291 (2015), 261–269.

15. T. Jahnke et al., Performance and degradation of proton exchange membrane fuel cells: State of the art in modeling from atomistic to system scale, J. Power Sources, 304 (1–2) (2016), 207–233.

16. J. M. Andújar et al., Comprehensive diagnosis methodology for faults detection and identification, and performance improvement of air-cooled polymer electrolyte fuel cells, Renew. Sustain. Energy Rev., 88 (2018), 193–207.

17. J. Luna et al., Nonlinear predictive control for durability enhancement and efficiency improvement in a fuel cell power system, J. Power Sources, 328 (2016), 250–261.

18. Z. You et al., Study on air-cooled self-humidifying PEMFC control method based on segmented predict negative feedback control, Electrochim. Acta, 132 (20) (2014), 389–396.

19. D. Li et al., Maximum power efficiency operation and generalized predictive control of PEM (proton exchange membrane) fuel cell, Energy, 68 (4) (2014), 210–217.

20. Y. X. Wang et al., Temperature control for a polymer electrolyte membrane fuel cell by using fuzzy rule, IEEE Trans Energy Convers, 31 (2) (2016), 1–9.

21. S. Strahl et al., Performance improvement by temperature control of an open-cathode PEM fuel cell system, Fuel Cells, 14 (3) (2014), 466–478.

22. D. Li et al., On active disturbance rejection in temperature regulation of the proton exchange membrane fuel cells, J. Power Sources, 283 (2015), 452–463.

23. K. Ou et al., Performance increase for an open-cathode PEM fuel cell with humidity and temperature control, Int. J. Hydrogen Energy, 42 (50) (2017), 29852–29862.

24. T. Wang et al., Hydrogen consumption minimization method based on the online identification for multi-stack PEMFCs system, Int. J. Hydrogen Energy, 44 (11) (2019), 5074–5081.

25. T. Wang et al., Efficiency extreme point tracking strategy based on FFRLS online identification for PEMFC system, IEEE Trans Energy Convers, 34 (2) (2018), 952–963.

26. Y. Liu et al., Protection and control of microgrids using dynamic state estimation, Protection Control Mod Power Syst, 3 (2018), 31–43.

27. C. Damour et al., On-line PEMFC control using parameterized nonlinear model-based predictive control, Fuel Cells, 14 (6) (2014), 886–893.
AUTHOR BIOGRAPHIES

Liangzhen Yin (S'16) received his B.S. degrees in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 2015. He is now currently working toward the Ph.D. degree in the School of Electrical Engineering, Southwest Jiaotong University. His research interests include fuel cell optimal control and energy management.

Qi Li (M'12-SM'15) received his B.S. degree and Ph.D. degree in Electrical Engineering School from Southwest Jiaotong University, Chengdu, China, in 2006 and 2011. He did research as visiting scholar in the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore, from 2009 and 2011. He is now a professor in the School of Electrical Engineering, Southwest Jiaotong University. His research interests include fuel cell locomotives optimal control, energy management strategy of hybrid system, and power system stability and control.

Tianhong Wang (S'17) was born in Sichuan, China. She received the B.S. degrees in electrical engineering from Southwest Jiaotong University, Chengdu, China, in 2016. He is now currently working toward the Ph.D. degree in the School of Electrical Engineering, Southwest Jiaotong University. His research interests include fuel cell modeling and optimal control, DC/DC converter control, energy management strategy of hybrid system.

Lu Liu (S'17) received her B.S. degree in Electrical Engineering School from Southwest Jiaotong University, Chengdu, China, in 2016. She is now currently working toward the M.S. degree in the School of Electrical Engineering, Southwest Jiaotong University. Her research interests include fuel cell optimal control and energy management.

Weirong Chen (M'99-SM'16) received his B.S. degree and M.S. degree in electronic engineering from Electronic Science and Technology University, respectively in 1985 and 1988, and the Ph.D. degree in power system and its automation from Southwest Jiaotong University in 1998, Chengdu, China. He is as Senior Visiting Scholar at Brunel University in 1999, England. Currently, he is IET Fellow, and is a professor in the School of Electrical Engineering, Southwest Jiaotong University. His research interests include renewable energy and its applications, fuel cell locomotive technology, and power system control. He has published more than 120 refereed journal and conference papers, 6 books, and is the holder of more than 40 Chinese patents.

How to cite this article: Yin L, Li Q, Wang T, Liu L, Chen W. Real-time thermal management of open-cathode PEMFC system based on maximum efficiency control strategy. Asian J Control. 2019;21:1796–1810. https://doi.org/10.1002/asjc.2207