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Advanced thermal management of automotive fuel cells using a model reference adaptive control algorithm

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ABSTRACT

Temperature control is a critical issue to ensuring the reliable performance of fuel cell systems. However, nominal feedback controllers currently used to regulate system temperature have limitations, due to the high inherent nonlinearity in the systems, and uncertainty in the parameters of the models, especially in the presence of dynamic load variations. In this study, a feedback controller was designed including Model Reference Adaptive Control (MRAC) to address uncertainties and robustly control the stack and the coolant inlet temperature in a proton exchange membrane fuel cell (PEMFC). The proposed controller was then evaluated by comparison with a nominal feedback controller. It was shown that if the parameters vary in the system the MRAC algorithm yields improved transient performances in terms of recovery speed and deviation in comparison to the nominal feedback control algorithm. The MRAC provides enhanced robustness.

Introduction

A fuel cell is a device that converts chemical energy into electrical energy, producing electricity, water, and heat without fossil fuels. For these reasons, fuel cells have been widely investigated as an alternative energy source [1–3]. Among the various types of fuel cells, the proton exchange membrane fuel cell (PEMFC) has demonstrated advantages in high power density, efficiency, low operating temperature, and fast start-up compared to other types of fuel cells [4–10].

In order to ensure satisfactory system performance, PEMFCs used in automotive applications must be controlled to operate in a wide range of conditions of mass flow, pressure, humidity of gas, and stack temperature. To accomplish this, it is important to accurately measure these system states using sensors (flow-meter, pressure, and thermocouples, etc.). This

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Nomenclature

A	Current, A
F	Faraday constant, C
n	Number of cells, -
ω	Motor speed, rad/s
J	Motor inertia, kg m^2
τ	Torque, N-m
θ	Valve position, degree
h	Enthalpy, kJ/kg
ε	Effectiveness, -
NTU	Number of transfer unit, -
Q	Heat transfer, W
p	Pressure, Pa
T	Temperature, K
m	Mass flow rate, kg/s
S	Sonic velocity, m/s
f	Valve fraction, fraction(0~1)
j	Current density, A/cm^2
E	Electric potential, V
R	Local resistance, Ω cm^2
U	Impeller speed, m/s
χ	Cathode over-potential, V
r	Specific heat ratio
σ	Electric conductivity
λ	Average water activity

Subscripts and superscripts

des	Desired value
air	Air
comp	Compressor
mt	Motor torque
lt	Motor load torque
in	Inlet
out	Outlet
ind	Inducer
o,c	Ideal specific enthalpy
H	Heat side
M	Mass side
gen	Heat generation
g	Gas side
cool	Coolant side
conv	Convection
amb	Ambient condition
FC	Fuel cell
RV	Reservoir
mix	Mix
byp	Bypass
rad	Radiator
p	Plant model
r	Reference model
mem	Membrane
Nern	Nernst voltage
eta	Additional losses
sto	Stoichiometry, -
imp	Impeller

information is then fed back to controllers, which apply the proper controls using actuators. In particular, due to the difficulty of directly measuring stack temperature, the accurate measurement of the coolant inlet and outlet temperatures is critical for maintaining the proper stack temperature.

Also, the system's operation can produce some disturbances, including sensor noise, uncertain parameters, and changing environmental conditions. These dynamic disturbances can cause the designed cooling controller to fail to properly manage temperature. For this reason, it is necessary to develop a control system that can operate robustly against disturbances, such as parameter uncertainty and change in ambient conditions.

Many control strategies have been reported in the literature which focus on methods of controlling the fuel cell system temperature. Li et al. used an extended state observer to estimate disturbances, the PEMFC temperature was stabilized via active disturbance rejection control [11]. Binrui et al. designed the temperature control of a PEM fuel cell by including a fuzzy incremental PID. The designed control was tested to find the optimal temperature point [12]. Kurz et al. developed a PI control to control the stack temperature. He also proposed an air flow control method to ensure the system performance [13]. Cheng et al. developed a control-oriented model to conduct model-based control using feed-forward and feed-back control. That study's aim was to maintain the cooling water temperature of a city bus [14]. Pohjoranta et al. applied generalized predictive control (GPC) to control the maximum temperature of a SOFC stack. The proposed GPC was compared with a conventional proportional-integral-derivative control [15]. Zhiyu et al. proposed an air-cooled self-humidifying method to achieve optimal system performance by controlling the stack temperature [16]. Hosseinzadeh et al. presented a water and thermal management approach to evaluate the effect of cooling inlet, outlet temperature and temperature gradient [17]. Gasser derived a state space model to regulate stack temperature and reservoir temperature. He designed a cooling system controller using the state feedback control method, and validated it through experiments [18]. Hwang proposed a thermal control algorithm to optimize the coolant inlet temperature. Also, he proposed that the optimal coolant inlet temperature range to ensure system performance was 58–63 °C [19]. Saygili et al. designed a model based temperature controller. The designed control algorithms were evaluated in terms of performance and parasitic power [20]. Also, Kunde et al. presented controls of both the humidity and the temperature of a micro PEMFC system while using only the airflow of the blower. A simulation using the proposed model was compared to experimental results. Then, the controller was designed and tested [21]. Shahsavari et al. presented a 3D numerical thermal model to analyze the heat transfer in a fuel cell system. Also, the thermal performance of the stack was investigated [22].

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