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Study on an adaptive multi-model predictive controller for the thermal management of a SOFC-GT hybrid system

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Abstract. A SOFC temperature control system based on adaptive multi-model predictive control (MMPC) method is designed for a solid oxide fuel cell-gas turbine (SOFC-GT) hybrid system with anode and cathode ejectors. Two multi-input and multi-output MPCs (under 100% and 90% load) are designed to control the anode and cathode inlet temperatures. The accuracy of the identified linear models are both more than 95%. The control performance of the designed MMPC is compared with a single MPC and traditional PI. The comparison results demonstrate that the proposed MMPC is most effective and competitive in SOFC thermal management. During the load following, the controller overshoot is less than 1.19K. The settling time is about 2000s, and the integral of time-weighted absolute error is less than 472.

1 Introduction

Solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems have the advantages of high efficiency, low emission, and flexible fuel [1-4]. However, the SOFC-GT hybrid systems are highly nonlinear and strongly coupled. In addition, the SOFC operation temperature would vary largely under a wide range of load conditions, which affects the lifetime and performance of the SOFC-GT system [5, 6]. Therefore, it is necessary to develop a robust SOFC temperature controller to ensure long-term safe and efficient operation.

In the past few decades, many researchers have investigated various temperature control strategies for different SOFC-GT systems. Ferrari [7] designed a feedforward-feedback controller to address the huge SOFC thermal inertia. The SOFC temperature control performance is improved during the load following. Zaccaria et al. [8] proposed a SOFC temperature control system by employing a preheat combustor to address the quite slow control problem of adjusting SOFC air flow rate. McLarty et al [4] designed a cascade temperature control strategy to both control the SOFC inlet and outlet temperatures over a wide dynamic range. Moreover, considering the high nonlinearity of the SOFC-GT hybrid systems, several advanced control methods have been applied to achieve better SOFC temperature control performance during load following. Wang et al [9] designed a fuzzy

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controller to self-tune the parameters of the SOFC temperature gradient controller to achieve safe operation of a SOFC-GT hybrid system. Restrepo et al. [10] designed a model predictive controller (MPC) to control the cathode side parameters for a SOFC-GT hybrid system. The model of MPC was identified according to experimental data of the hybrid performance (HyPer) facility at NETL. Tsai et al. [11] applied a multi-model adaptive control methodology for the SOFC-GT HyPer facility. The designed adaptive controller realized a wide operation envelope. Ferrari et al. [12, 13] proposed an advanced control strategy by coupling the MPC and PID to mitigate the SOFC temperature variation during the load following. The control performance was validated by the cyber-physical facility at the University of Genoa.

The above investigations showed that the MPC can perform better control capability than traditional PI to mitigate the SOFC temperature variation in a SOFC-GT hybrid system. However, the above literature neglects the temperature difference between different layers (such as the anode layer and cathode layer). Recently, our previous works [14-16] pointed out that the SOFC temperature on anode layer is significantly different from the cathode layer. The anode-cathode temperature could research 92.8 K, which would damage the SOFC cell. Accordingly, a two-loop temperature control strategy of both controlling the anode and cathode inlet temperatures was proposed to increase the reliability and lifetime of the SOFC system.

Continuing our previous works, this paper intends to put forward a novel two-side SOFC temperature control system, using MPC rather than PI, for a SOFC-GT hybrid system with two ejectors. Furthermore, an adaptive multi-MPC method is established to deal with the high nonlinearity.

2 Methodology

2.1 System description

The SOFC-GT hybrid system with anode and cathode ejectors is shown in Fig.1, which has been designed in our previous work [17]. In the SOFC thermal management system, the anode and cathode inlet temperatures are both controlled by adjusting the rotational speed set point and the fuel flow rate delivery to the after burner. In addition, the rotational speed is controlled by a fast controller to rapidly track its set point.

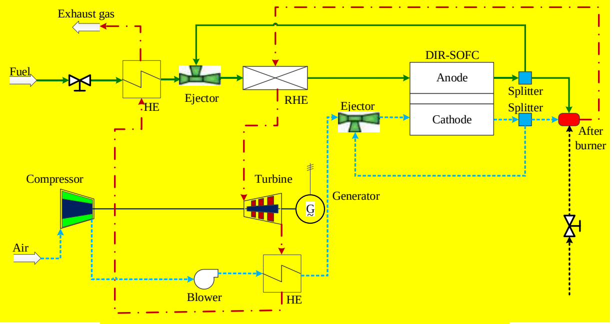

Fig. 1. Schematic of the SOFC-GT system

2.2 Adaptive MMPC method

The operation condition of a SOFC-GT system may be changed with the load and external environment. An adaptive MMPC structure is designed as shown in Fig. 2. The approach of multiple models is applied to avoid the model mismatch within a wide operation range. The wide operation range is divided into multiple operation conditions. A corresponding MPC is designed for each operation condition. The suitable MPC is matched according to the operation condition. For the MPC predictive model, its inputs are the fuel flow rate of after burner and gas turbine speed, and the outputs are the anode and cathode inlet temperatures.

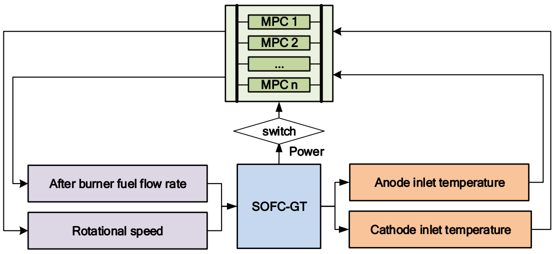

Fig.2. Structure of MMPC system

In this paper, a MMPC of two different operation points (100% and 90% system load) is developed by the Matlab MPC toolbox, which is based on the quadratic cost function and the active-set optimization algorithm.

$$J(k)=\sum_{i=0}^{N-1}(y(k+i)-y_r)^T Q_0(y(k+i)-y_r)+\sum_{j=0}^{M-1}\Delta u(k+i)^T R_0\Delta u(k+i)$$

$$\begin{aligned} s.t.\quad & x(k+1)=Ax(k)+Bu(k) \qquad y(k)=Cx(k)+Du(k) \\ & u_{\min}\le u(k+i)\le u_{\max} \\ & \Delta u_{\min}\le \Delta u(k+i)\le \Delta u_{\max} \end{aligned} \tag{1}$$

Where J is the cost function, N is the prediction horizon, M is the control horizon.

The linear prediction models at 100% and 90% system load are identified in terms of transfer functions. Due to lacking massive commercialization of SOFC-GT systems and availability of experimental data, the validated mechanism model from our previous work [17] is taken as a physical SOFC-GT system. The mechanism model includes one dimensional SOFC model with four temperature layers, ejector model, compressor and turbine models, lumped blower and after-burner models, and one dimensional heat exchanger model. The prediction models are identified by the simulation data which is collected through the step responses.

$$G_1=\begin{bmatrix} \dfrac{1.98*10^{-2}}{s+4.275*10^{-4}} & \dfrac{3.869*10^{-2}s-2.209*10^{-6}}{s^2+3.506*10^{-1}s+1.201*10^{-4}} \\ \dfrac{7.04*10^{-3}}{s+2.994*10^{-4}} & \dfrac{-5.42*10^{-4}s-4.127*10^{-7}}{s^2+4.528*10^{-3}s+1.736*10^{-6}} \end{bmatrix} \tag{2}$$

$$G_2=\begin{bmatrix} \dfrac{1.739*10^{-2}}{s+2.958*10^{-4}} & \dfrac{0.1911s+1.249*10^{-6}}{s^2+0.9402*10^{-6}s+2.062*10^{-4}} \\ \dfrac{8.89*10^{-3}}{s+2.003*10^{-4}} & \dfrac{-6.008*10^{-4}s-2.725*10^{-7}}{s^2+2.306*10^{-3}s+4.675*10^{-7}} \end{bmatrix} \tag{3}$$

Considering the overload condition, the identified G_1 is the transfer function matrix under 100% load (328.0 kW), used to represent 105%~95% load range. G_2 is the transfer function matrix under 90% load (295.2 kW), used to represent 95%~85% load range. The accuracy of the identified predictive model G_1 is more than 95.11% and the accuracy of G_2 is more than 96.47%. On the basis of identified predictive models, two MPCs are designed respectively.

3 Comparison of difference temperature control schemes

The control performance of the designed MMPC controller is compared with a single MPC controller and traditional PID controller. The parameters of the single MPC controller are designed according to the prediction model G_1 at 100% system load. Due to the long time-scale (thousands of seconds) of the SOFC-GT temperature response, the prediction horizon should be longer to capture more look-ahead information. In this paper, the prediction and control horizons of the MPC and MMPC are 100 s and 2 s. The PI parameters are obtained by the Ziegler-Nichols tuning method, which has been successfully applied to a SOFC-GT hybrid system [7, 18].

As to the PI control scheme, the time-scale characterization of the SOFC-GT transient phenomena makes the thermal management system often to use a slow PI controller, avoiding the derivative part [19]. The parameters of two PI controllers are shown as follows.

- Anode inlet temperature controller: K_P = 0.0015; K_I = 750;
- Cathode inlet temperature controller: K_P = 1300; K_I = 800.

In order to verify the ultimate capabilities of designed controllers, the SOFC-GT mechanism model is applied to verify the capabilities of designed controllers when the fuel flow rate steps from 0.0109kg/s to 0.0095kg/s (corresponding to 100%~93.5% load range). The anode and cathode inlet temperatures are both controlled at 1073 K in the SOFC thermal management system.

The performance of the anode inlet temperature control loop is illustrated in Fig. 3. From the response of after burner fuel flow rate, an observation is that PI control has the worst stability performance. It took the longest time to stabilize the after burner fuel flow rate. Both the MPC and MMPC schemes lead to a rapidly response.

The temperature responses regulated by after burner fuel flow rate are also presented in Fig. 3. The reduction of after burner fuel flow rate leads to a decrease in the generated heat of the electrochemical reaction. However, the temperature of reflux exhaust does not change significantly due to the slow internal heat transfer process in the SOFC. Therefore, the anode inlet temperature of SOFC rises rapidly. When the reflux exhaust temperature decreased with the drop of fuel flow rate, the anode inlet temperature slowly decreases to 1073 K. PI control has a certain degree of oscillation, which cause a long control time (about 2596 s). The prediction model mismatch of MPC causes a great overshoot. Correspondingly, MPC would take about 4636 s to research a stable state. As to MMPC, the system could be controlled in a stable state within 614 s. The overshoot was kept within 1K during the dynamic process.

During the SOFC temperature control process, the maximum temperature gradient in anode channel decreases from 9.2K/cm to 8K/cm. In the early stage of the control process, the internal reaction of the SOFC is severe, and the maximum temperature gradient also changes dramatically. As the fuel flow rate decreases, the maximum anode temperature gradient decreases. The MPC and MMPC can control the maximum temperature gradient effectively. However, the maximum temperature gradient reaches 9.8 K/cm under the PI control. The PI controller likely to lead to the maximum temperature gradient exceeding 10K/cm under a large-scale load step, and may damage to the SOFC cells.

The cathode temperature control performances under three control strategies are shown in Fig. 4. The change of rotational speed is within the safe range under the effect of all control schemes. The system with MPC has the largest rotational speed variation. The rotational speed decreases to 64100 r/min and then stabilizes at 66000 r/min. The MMPC control scheme can guarantee the smallest rotational speed variation.

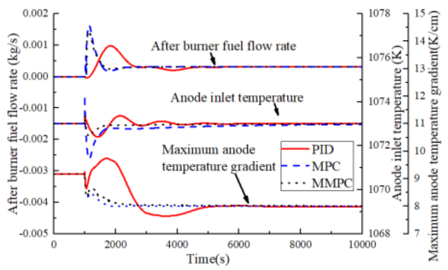

Fig. 3. Anode temperature control performance

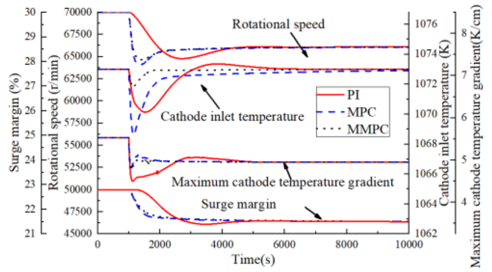

Fig. 4. Cathode temperature control performance

The reduction of the rotational speed helps reduce the air flow rate in the cathode channel. The PI control strategy adjusts the rotational speed slowly. Therefore, the system is stabilized within about 4316 s. MPC and MMPC can adjust the cathode inlet temperature to the expected value quickly. However, in the control process of MPC, the cathode inlet temperature drops greatly at the moment of 1000s due to the mismatch of the MPC model. The MPC overshoot can research 4.32 K, while MMPC overshoot is only 1.19 K. The larger overshoot causes that the MPC takes about 8568 s to reach steady state. However, the MMPC only takes about 765 s. The maximum temperature gradient in cathode channel also decreases from 5.5 K to 4.9 K due to the decrease of generated heat of electrochemical reaction.

The surge margin responses are also illustrated in Fig. 4. The surge margin highly relates to the rotational speed. As a result, it slowly drops from 22.78% to 21.5% due to the reduction of rotational speed. However, all three controlles can ensure the surge margin far away from the threshold of 15% during the dynamic process.

All the simulation results are summarized in Table 1 for comparison of the three schemes. To evaluate the control capability, three parameters in terms of overshoot, settling time t_s and integral of time-weighted absolute error (ITAE) are applied. The settling time t_s is defined as the time to keep the final controlled temperature within ± 0.1K. The ITAE criterion is also an important index to evaluate the rapidity and stability of a controller, which is defined as follows :

$$ITAE = \int t\left|e(t)\right| dt \tag{4}$$

Where t is the sampling time, e is the error from set-point.

Table 1. Control performance comparison of different control schemes.

Parameters	PI	MPC	MMPC
Maximum anode-cathode temperature difference [K]	2.51	2.81	0.63
Overshoot of anode temperature control [K]	0.60	1.54	0.56
Overshoot of cathode temperature control [K]	2.87	4.32	1.19
t_s of anode temperature control [s]	2596	4636	614
t_s of cathode temperature control [s]	4316	8568	756
ITAE of anode temperature control [$K\cdot s^2$]	302	734	199
ITAE of cathode temperature control [$K\cdot s^2$]	1963	2228	472

The largest overshoot occurs in cathode temperature under the effect of MPC scheme and is 4.32 K. The lowest settling time, ITAE, and anode-cathode temperature difference make the MMPC most competitive. In summary, MMPC is the best scheme to keep a constant SOFC-GT internal temperature profile. MMPC has been proven to have superior performance in terms of speed and stability, with a much smaller overshoot and settling time, as well as the smallest ITAE.

4 Conclusions

This paper proposed an adaptive MMPC appraoch both controlling the anode inlet temperature and cathode inlet temerature for a SOFC-GT hybrid system. The conclusions are as follows.

(1) A thermal management system based on an adaptive MMPC is designed for a SOFC-GT system to improve the capability of mitigating internal temperature variation. The most suitable MPC can be matched according to the system power in the wide operation range.

(2) An identified predictive model is developed for the construction of MMPC based on the simulation data collected from the validated mechanism model in our previous work. The accuracies of obtained transfer functions are more than 95.11%.

(3) The proposed MMPC has the best performance in terms of rapidity and stability with a much smaller overshoot (less than 1.19K), shorter settling time (about 2000s), and the smallest ITAE (199 $K \cdot s^2$ for anode temperature control and 472 $K \cdot s^2$ for cathode temperature control).

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