International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1054

PERFORMANCE DEGRADATION AND FAULT PREDICTION BASED SOLID OXIDE FUEL CELL SYSTEM OPTIMUM CONTROL

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ABSTRACT

Solid oxide fuel cell (SOFC) technology has the advantages of high efficiency, low emission and fuel flexibility, but high cost and short lifetime are still the bottlenecks hindering its large-scale commercial application. The performance of SOFC systems will gradually evolve into faults in the long run, leading to variation of the dynamic and static characteristics of the system. The control system designed according to the original system characteristic would face with problems such as parameter mismatch, inaccurate control and even wrong control laws. In this paper, based on a 1kW steam-reforming SOFC system multi-mode model, the dynamic and static characteristics of SOFC systems under the condition of performance degradation and fault evolution are investigated, and a complete health evaluation system is developed for the first time in the SOFC field to optimize the system control and identify early faults for the pre-treatment. The simulation results show that with the improved system controller higher system efficiency and longer lifetime of the SOFC system could be achieved, dealing with the performance degradation and fault evolution mechanisms in reality.

Keywords: SOFC system, Performance degradation, Fault evolution, Multi-mode model, Health evaluation system, Control optimization

1. INTRODUCTION

Solid oxide fuel cell (SOFC) technology is considered as one of the most promising green power generation technologies in the 21st century [1]. However, high cost and short lifetime are still the bottlenecks hindering its large-scale commercial application [2], which results from the changes in the dynamic and static characteristics of the system due to the degradation and fault mechanisms.

If an effective control is expected to be achieved, the state of health for SOFC systems has to be accurately evaluated. However, there are few researches involving the issues. For example, Dolenc et al. [3] proposed an integrated approach for state of health estimation based on stack's ohmic area specific resistance, which was validated with experimental data from a 10kW SOFC system.

In addition, SOFC system control schemes could be divided into two types: decentralized and centralized. Most of the former designs contained one or two control loops for power and temperature control [4]. For instance, Stiller et al. [5] presented a feedforward-feedback multi-loop PID control strategy for an SOFC-GT hybrid system. Wu and Zhu [6] proposed an adaptive PID decoupling control scheme for temperature control, an MPC scheme for power control, and a single neuron adaptive PID control scheme for fuel utilization control, respectively. With regards to centralized control, Jiang et al. [7] proposed a novel control strategy to cooperatively maintain thermal constraints and optimize system efficiency while conducting fast load following. Sanandaji et al. [8] developed a locally linear parameter varying based MPC controller and a standard PID controller was separately designed for the temperature control.

These researches provided a broad range of methods for SOFC system control. Nevertheless, they did not fully consider the performance degradation and fault evolution mechanisms. In this paper, an SOFC system multi-mode model considering degradation and fault mechanisms was introduced. The dynamic and

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).

static characteristics under performance degradation and fault evolution were investigated with the help of optimal operation point (OOP). A complete health evaluation system was developed to optimize the system control coping with long-term performance degradation and identify early faults for the pre-treatment.

2. SOFC SYSTEM MULTI-MODE MODEL

The original mechanism model of the system was obtained by connecting the sub-models of the key components, which were illustrated in the references [9, 10]. Then Matlab/Stateflow platform, which was a simulation environment based on finite state machine and flow chart, was used as the main tool to integrate the performance degradation and fault evolution mechanisms into the original system model. The multi-mode model was validated with the experimental data obtained from the three long-term system tests, and the validation results demonstrated the accuracy and reliability of the model.

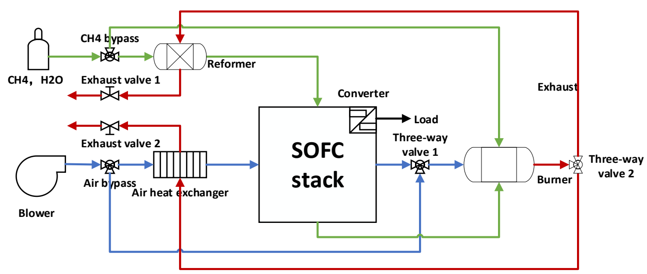

Fig.1 Layout of the 1kW steam-reforming SOFC system

3. PERFORMANCE DEGRADATION BASED ANALYSIS

The OOP of SOFC systems under performance degradation was defined as the input set that enabled the system with a specific degradation state to meet temperature constraints and the power demand and to maximize the system efficiency in steady state.

System efficiency was the core parameter in the optimization process and was defined as the objective function. The temperature constraints of the SR-SOFC system consisted primarily in the burner, the reformer and the stack. The GA-PSO algorithm was selected to search for the optimal solution [11].

Through the optimization method above, the OOPs under various performance degradation conditions were obtained. The drift functions of the OOPs were acquired by means of function fitting and mapping models, which indicated the quantitative relationship among the OOPs, the net output power of the system and the performance degradation parameter, as shown in Table 1.

Table 1. Final results of the drift functions

Input	Fitting functions
U	$P_{net} \in [0,100]$, $U = 0.8$; $P_{net} \in (100,800)$, $U = \max\{0.7927 - 0.0001635P_{net}$ $-0.01815r_{dr}, 0.7\}$; $P_{net} \in [800,1000]$, $U = 0.7$
Pr	$\mathrm{Pr} = 0.03509 + 0.0008127P_{net} - 0.05284r_{dr} +$ $0.0001108P_{net}r_{dr} - 4.796\times10^{-7}P_{net}^2$
BP1	$BP1 = 0$
BP2	$P_{net} \in [0,500]$, $BP2 = 0$; $P_{net} \in (500,1000]$, $BP2 = -0.06846 + 0.0001299P_{net}$ $-0.0836r_{dr} + 0.0001392P_{net}r_{dr} - 0.02298r_{dr}^2$
F_fuel	$F\_fuel = 0.09951 + 0.001337P_{net} - 0.04579r_{dr}$ $+0.0002113P_{net}r_{dr} + 1.004\times10^{-6}P_{net}^2$
F_air	$P_{net} \in [0,300]$, $F\_air = 0.015$; $P_{net} \in (300,1000]$, $F\_air = \max\{1.21\times10^{-7}P_{net}^2$ $-6.782\times10^{-5}P_{net} + 0.02479, 0.015\}$

4. SYSTEM ANALYSIS UNDER FAULTY CONDITIONS

4.1 Analysis method

Table 2. Summary of fault response characteristics

Fault type	Fault response characteristics of key variables			
	P_{net}	T_B	T_R	T_S
1	−	−	−	−
2	−	+	+	+
3	/	/	+	/
4	−	/	/	−
5	−	/	−	−
6	/	/	/	/

For each fault evolution mechanism, three cases with different fault degrees were simulated, namely 0.025, 0.05 and 0.1. The fault degree of the components in the original model was regarded as 0. The OOPs at 1000W (full load) and 500W (half load) were selected as the representative power points to analyze the responses of the SOFC system to the faults. Net output power (P_{net}), burner temperature (T_B), reformer temperature (T_R) and average temperature in the stack (T_S) were chosen to be the key variables to observe the fault responses, because they reflected the power and heat generation state of the system as well as the main temperature constraints during operation.

4.2 Dynamic and static characteristic analysis

The response curves of gas leakage at the anode inlet (Fault type 1) at 1000W are taken as the example to be shown in Fig. 2. After the introduction of the fault, all the key variables show a downward trend and gradually enter the steady state, for which no temperature constraint would be violated in the response process. It is noticeable that at 1000W with the fault degree of 0.05 or 0.1, each variable does not converge to the globally stable equilibrium point directly, but experience a stable equilibrium point in the middle of the dynamic process.

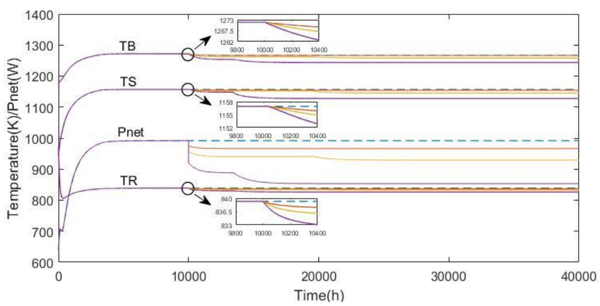

Fig. 2 Response curves of gas leakage at the anode inlet at 1000W. The blue dotted lines represent the original case, while orange, yellow and purple solid lines represent the cases with the fault degrees of 0.025, 0.05 and 0.1, respectively.

4.3 Summary of SOFC system fault response characteristics

With all the previous analysis, the response characteristics of the different faulty conditions could be identified with the variation modes of the key variables, which is summarized in Table 2, where '+' represents that the steady-state relative change is always positive and the maximum amplitude exceeds 1%, '-' represents that the steady-state relative change is always negative and the maximum amplitude exceeds 1%, and '/' means that the sign of the steady-state relative change is indefinite or the maximum amplitude is below 1%. For each fault, the key variables marked with '+' '-' could be selected as the characteristic parameters.

5. HEALTH EVALUATION SYSTEM BASED SYSTEM CONTROL IMPROVEMENT

5.1 Health evaluation system for SOFC systems

With the identical initial working condition and real-time inputs, the ratio of the current functional efficiency of the system or component to the original one (with no degradation and no fault) is defined as the health degree of the system or component, which could be expressed as:

$$hd = \frac{\eta}{\eta_0} \tag{1}$$

where *hd* is the health degree of the system or component, η is the current functional efficiency, and η_0 is the original functional efficiency. The function of the health degree of the system or component to time is defined as its health degree degradation function, which is denoted as *hd(t)*. If the health degree degradation function of the system or component is derivable, the derived function of the health degree degradation function is defined as the health degree degradation rate function, which could be expressed as:

$$hdr(t) = \frac{d[hd(t)]}{dt} \tag{2}$$

where *hdr(t)* is the health degree degradation rate function of the system or component. The health evaluation system the SOFC system in this work could be denoted as:

$$HES = \begin{bmatrix} hd_r,\ hd_r(t),\ hdr_r,\ hdr_r(t), r_{dr}; \\ hd_{st},\ hd_{st}(t),\ hdr_{st},\ hdr_{st}(t); \\ hd_{sys},\ hd_{sys}(t),\ hdr_{sys},\ hdr_{sys}(t) \end{bmatrix} \tag{3}$$

5.2 Health evaluation system based control improvement

The basic control design discussed in this work was the system controller described in [7]. The feedforward part of the basic power tracking controller was replaced with the OOP drift functions to update the real-time OOP according to the degradation status of the system. The simulation results indicated that the improved controller could finish the task of power tracking in the overall performance degradation process, while the original controller would fail due to the failure of power tracking, as shown in Fig. 3.

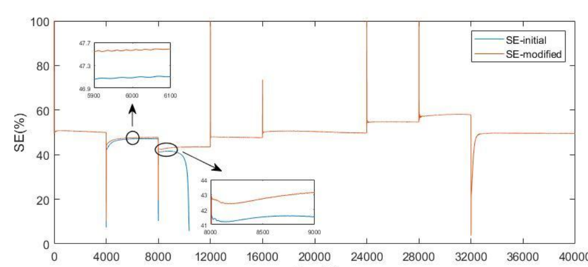

Fig. 3 System efficiency before and after the controller improvement to deal with degradation mechanisms: 'initial' and 'modified' represent the cases before and after the improvement, respectively.

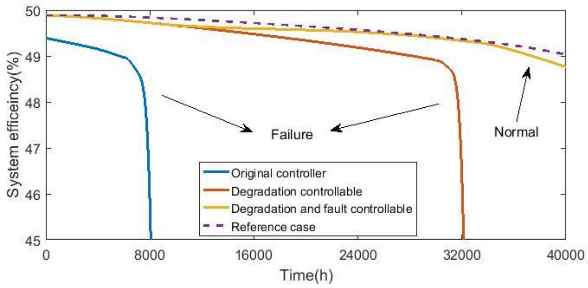

Fig. 4 Control effect diagram of the early fault identification and treatment controller.

On the other hand, the health degree of the system could be fitted as a linear function of the health degrees of the reformer and the stack, due to their logical correlation. It was indicated that compared with the fitting result in the fault-free case, the result under each faulty condition nearly formed a specific migration pattern, which could be used to identify the early fault and even estimate the fault degree in the future work. Here, carbon deposition in the reformer (Fault type 2) is selected as the typical faulty case to show the effects of efficiency improvement and lifetime expansion of the early fault identification and treatment controller (Fig. 4).

6. CONCLUSION

In this work, the drift characteristics of optimal operation points (OOPs) were quantitatively expressed as the drift functions. The dynamic and static response characteristics of six common faults were analyzed and summarized. The health evaluation system of SOFC systems was developed, based on which the control improvement strategies to cope with performance degradation and fault evolution mechanisms were proposed and validated by simulation. The results indicated that the improvements on the system controller could expand the lifetime of the system, raise the system efficiency evidently (up to about 2%), and have the potential to pre-treat faults and lower the costs of maintenance and replacement.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China (61773174, 61873323, 61573162), the Hubei Province Natural and Science Foundation (2017CFB4165, 2016CFA037). Thanks for the basic work from the workmates in my lab and fuel cell innovation center, Huazhong University of Science and Technology.

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