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Solid oxide fuel cell stack temperature estimation with data-based modeling – Designed experiments and parameter identification

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HIGHLIGHTS

- A linear, dynamic model for SOFC stack temperature is identified from experimental data on complete 10 kW SOFC system.
- Accurate temperature estimation is obtained with the identified model and Kalman filtering.
- Experiment design and all algorithms are given in a ready-for-implementation manner.

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ABSTRACT

Data-based modeling is utilized for the dynamic estimation of the temperature inside a solid oxide fuel cell (SOFC) stack. Experiment design and implementation, data pretreatment, model parameter identification and application of the obtained model for the estimation and prediction of the SOFC stack maximum and minimum temperatures are covered. Experiments are carried out on a complete 10 kW SOFC system to obtain data for model development. An ARX-type (autoregressive with extra input) polynomial input–output model is identified from the data and Kalman filtering is utilized to obtain an accurate estimator for the internal stack temperatures. Prediction capabilities of the model are demonstrated and using the modeling approach for SOFC system monitoring is discussed.

1. Introduction

Thermal management of solid oxide fuel cell (SOFC) stacks is essential for the successful deployment of SOFC based power systems. The general temperature level as well as the temperature distribution inside the SOFC stack affect both the stack performance and the rate of stack performance degradation [1,2]. Therefore, it is fundamentally important to keep the stack temperature within a given range. To this end, it is necessary to have means for either measuring or estimating the temperature at various locations inside a SOFC stack. Installing temperature measurement devices directly in the stack is possible but adds to the system's complexity, thus increasing its price and decreasing its reliability. Estimating the stack temperature by using computational models leaves the system hardware intact but requires the effort of model development and deployment into system environment.

SOFC stack models based on physical first principles have proven very useful during the system design phase when an actual apparatus does not yet exist and the system operation must be studied over a wide, undefined operating envelope. However, as soon as the system is up and running it is often more efficient to create system-specific models based on measured system data. Data-based models, such as the polynomial input–output (I/O) models utilized in this work, are simple to identify and run, and their application-specific accuracy can surpass that of physics-based models. The main challenge in creating data-based models is in collecting representative data of the modeled process. The design of experiments methodology is useful in solving the conflict between data information content and cost of experimental effort. This paper documents the process of designing experiments for gathering data from a complete 10 kW SOFC system and using that data for model parameter identification and model validation. Finally, the identified model is utilized to estimate and predict the temperature inside the SOFC stack.

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1.1. State of the art

The SOFC power system technology is still relatively young and presumably therefore the vast majority of SOFC models found in the literature are based on physical first principles. Numerous very advanced models have been published and extensive reviews of the SOFC modeling work based on 1st principles are found e.g. in Refs. [3–6]. The model outputs typically cover both the electrical variables (voltage, current, power) as well as the temperature (and the temperature distribution) within the SOFC. Fluid dynamics are also commonplace in physical SOFC models, which enables the analysis of flow and pressure fields in the modeled device. Often the computational requirement for solving 1st principle SOFC models is high, restricting the level of model detail. Therefore, the models often focus on, e.g., a single repeating unit within the SOFC stack instead the whole stack, or are reduced in physical dimensions (from three to 0-2 dimensions).

Purely data-based models (a.k.a. black box models) of SOFCs have also been developed [[6], Section 5]. Most black box SOFC models published so far are based on some variant of so-called neural networks. Some recent developments also include Bayesian networks and statistical data analysis based on linear regression models [7–9]. An ARX-type (autoregressive with extra input) input/output polynomial model was used in Ref. [10] to implement the linear dynamic part in a Hammerstein-type SOFC model.

Black box models only simulate the outputs that were selected for modeling before data collection and the main restriction for black box model utilization stems from challenges with collecting proper data. Considering SOFC applications these challenges are mostly related to their very high operating temperature of ca. 600–900 °C. Typical applications of reported black box SOFC models include the simulation of the electrical output of the SOFC stack and the temperature, and sometimes pressure, at the stack outlets which are easier to measure than e.g. stack outlet gas composition or internal stack temperature values. In some cases the data for model development is measured from a single cell or a short stack in a dedicated test rig, or even produced by a physical model, in order to reduce the required experimental effort [6]. While these special arrangements for data acquisition are useful for the model development work, the so-obtained models are not directly applicable to complete SOFC stacks and systems.

The practical challenges related to the experimental work with SOFCs underline the importance of proper planning and execution of the data collection phase when developing black box SOFC models. The design of experiments methodology (DoE), covered in several textbooks such as [11], provides the analytical tools to optimize the amount of information that is obtained from the examined object with a given experimental effort. Within the field of fuel cell research, DoE has mainly been used for system behavior studies, especially in proton exchange membrane fuel cell (PEMFC) research [12–15]. In Refs. [9,16,17] DoE is utilized in particular for the analysis and the development of linear regression models of SOFCs.

1.2. Background and overview of this work

This work focuses on developing estimates of the stack temperature values inside a SOFC stack, by using linear dynamic, input/output (I/O) polynomial models whose parameters are identified from data. The aim of the work is to find such solutions that are practically feasible considering their implementation in embedded process control systems and their utilization for SOFC power system control.

The dependencies between internal SOFC stack temperatures and three system inputs, namely, load current, air flow and air temperature at stack module inlet, were experimentally evaluated in a preceding work [9,18]. The experiments were carried out around a single specified nominal operating point and the models were created for the steady state estimation of the stack temperature by utilizing multivariable linear regression (MLR). All the evaluated inputs were found to have a significant effect on the stack temperature, and the stack cathode outlet temperature was found vitally important for accurate stack temperature estimation. Also, an MLR model was utilized for stack temperature regulation, and a preliminary study on I/O model identification was carried out in Refs. [19,20].

In the current work, four system inputs are used in the experiments. These include the load current, air flow and air temperature at stack module inlet, as before, but also the system natural gas (NG) flow. The experiments were carried out in order to obtain such a series of data which enables creating models for the estimation of the stack temperature in both steady states as well as during transient operation over the whole relevant operating range (i.e. excluding start-up and shutdown). To meet these aims, the experiments were designed to fit within a pre-defined system operating space, and in particular, around two representative "central" operating conditions (Section 2). Thus, in comparison to the previous work [9,18], the data series collected and used in this study is larger in terms of the number of inputs as well as their range of variation. In addition, the number of data points collected is larger than before, which enables splitting the data set to a part used for model development and another part used solely for model validation.

The gathered data is utilized to identify a polynomial I/O model with the ARX structure. This model structure has the advantages that (i) the parameters' relationship to each input-to-output pair remains clear and (ii) the identification algorithm is very simple (Section 3.2). The obtained ARX model is re-cast to the state space format to enable simple utilization of the so-called Kalman filter [21] for the dynamic estimation of the temperatures (Section 3.4, 4.1). Finally, an optimal predictor for the stack temperature variables is built by utilizing the obtained estimate (Section. 3.5, 4.2) and applying the modeling approach to SOFC degradation monitoring purposes is briefly discussed (Section. 4.3).

2. Experimental

The experiments were carried out with a complete 10 kW SOFC system [22]. The system utilizes a single, planar, 80-cell SOFC stack produced by Versa Power Systems [23]. The stack is equipped with internal temperature measurement sensors. The system layout is illustrated in Fig. 1.

Load current (I, A), air flow ($\dot{V}_{\mathrm{air}}$, dm^3 min^{-1}), air temperature at stack module inlet ($T_{\mathrm{air,in}}$, °C) and system NG flow ($\dot{V}_{\mathrm{NG}}$, dm^3 min^{-1}) were considered as independent system inputs in the experiment design (the volumetric flow being measured in 101325 Pa and 0 °C). Stack maximum and minimum temperature ($T_{\max}$, $T_{\min}$, °C) and the cathode outlet temperature ($T_{\mathrm{cath,out}}$, °C) were recorded as response. The stack maximum and minimum temperatures were determined by taking the maximum and minimum, respectively, of the values measured with 13 temperature measurement sensors installed inside the SOFC stack and distributed over one representative cell, located in the middle of the stack. Thus, in fact, they are the cell maximum and minimum temperature and together provide a representative value of the temperature difference over the cell. An additional 10 temperature measurement sensors were distributed over the stack to be certain that the temperature