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Feedforward-feedback control of a solid oxide fuel cell power system

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ARTICLE INFO

Article history:
Received 1 December 2017
Received in revised form
29 January 2018
Accepted 31 January 2018
Available online xxx

Keywords:
SOFC power systems
Feedforward-feedback control
Control design and tuning
Load following operation
System efficiency
Fuel cell degradation

ABSTRACT

One of the main challenges for wide-spread utilization of the solid oxide fuel cell (SOFC) power systems is how to achieve high electrical efficiency without increasing the degradation rate of the fuel cells. To run the SOFC power system at high efficiency over a long period of time, properly designed controllers are indispensable.

Although a number of various approaches to control SOFC have been proposed so far, it seems that the design of control system, along with simple tuning procedure, has not been treated in a consistent manner. This issue is addressed in the present paper resulting in a feedforward-feedback control structure. The feedforward part is based on the stoichiometry of electro-oxidation, reforming and combustion reactions, which allow immediate response to variable current demand. The feedback part performs additional fine adjustment of fuel and air supply in order to minimize the undesired system temperatures variations. The selection of pairings of manipulated and controlled variables for control is based on physical knowledge of the system. Input/output pairing for single-loop feedback control is assessed by the relative gain analysis. An efficient procedure for tuning the parameters of the feedback controllers is suggested, relying on simple open-loop step responses of the system.

The proposed low-level control is assessed on a detailed physical model of a 2.5 kW SOFC power system by simulating two nonstationary load regimes. Simulations show that the control provides a robust operation under large load variations while meeting the operating constraints. Due to its simplicity, the control is feasible for implementation on a real SOFC system.

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https://doi.org/10.1016/j.ijhydene.2018.01.203

Introduction

The solid oxide fuel cell (SOFC) technology is a promising solution for the combined generation of electric power and heat. However, there are still obstacles which have to be overcome for wide-spread utilization of SOFC technology, e.g. to achieve a high electrical efficiency and a long life-time of the SOFC stack under realistic operating conditions [1,2].

SOFC power systems are complex devices since they are composed of various electrochemical (e.g. a stack of SOFCs), chemical (e.g. reformer), mechanical (e.g. air blower) and combustion (e.g. burner) components with strong mutual interactions. The efficiency of such a complex system is highly conditioned by the operational demands of all integrated components [1,2].

The key obstacles for a long operating life-time of the cells are a range of degradation phenomena [3]. Non-optimal operating regimes, e.g. improper thermal management of a stack or insufficient supply of fuel, air and water into the system, could accelerate the degradation processes and, or in the worst case, lead to the system malfunction [4].

In order to achieve a proper trade-off between the system efficiency and degradation rate, good controllers are indispensable. Their purpose is i) to supply enough fuel into the stack in order to achieve the required stack current and prevent fuel starvation in cells, ii) supply enough air into the stack to prevent air starvation in cells and to maintain stack temperature in order to reduce thermal stress, iii) supply enough water in the reformer which is needed for methane reforming process in order to prevent solid carbon deposition in cells and iv) supply enough fuel and air into the burner to heat up the reformer and incoming air [1].

Various low-level control structures for SOFC power systems have been proposed so far. In Ref. [5] a feedforward-feedback control strategy for rapid load following was proposed. Simulations indicate that the proposed control strategy provides rapid load following while maintaining the burner temperature within the safe range by manipulating the stack current. Controllers that prevent fuel starvation in SOFC systems were proposed in [6]. It is shown by means of simulation that fuel starvation can be prevented by using the rate limiters and reference governors when the load current changes rapidly. In Ref. [7] dynamic model was used to develop feedforward-feedback control strategies for both cold-start and warm-up operations of the SOFC power system. The authors focused on the problem of achieving a proper transition between cold start and warm-up phases. In Ref. [8] decentralized proportional-integral (PI) control was designed to control the stack voltage and fuel utilization of SOFC stack. The design procedure is based on a nonlinear model of SOFC stack and involves selection of control variables, input-output pairing selection and tuning of controllers. In Ref. [9] a generalized predictive controller was proposed to control the maximum temperature in an SOFC stack and the temperature difference over the stack. The proposed control is evaluated by simulation with various input-output pairings, with and without constraints. In Ref. [10] a time delay controller with an observer is presented to enhance the load-following capability without fuel starvation. The controller is verified on a model of the SOFC power system. In Ref. [11] a feedforward control of the SOFC power system with anode off-gas recycle is presented. It was experimentally verified that the proposed control allows secure operating conditions as well as maximization of the electrical efficiency. However, without using the feedback control, larger system temperatures variations were obtained. In Ref. [12] an analysis-based optimization method was proposed to optimize the efficiency of the SOFC system. Based on the results related to the efficiency optimization, a new stack control strategy was proposed to achieve temperature safety and high efficiency in steady state and with power switching transients. In Ref. [13], a real-time optimization strategy which combines the real-time optimization of electrical efficiency and model predictive control was verified on a dynamic model of the SOFC power system. Simulation results showed that near-optimality can be obtained and constraints can be respected despite model inaccuracies and large variations in load demand. In Ref. [14], the experimental validation of the real-time optimization strategy proposed in [13] was presented. It was shown that the real time optimizer, which applies the static model of the system, was able to converge quickly and safely towards the optimum efficiency. In Ref. [15] fault tolerance control of SOFC systems is proposed, which includes a fault diagnosis module, a decision-making part, and four backup nonlinear model predictive controllers. Simulation results showed that the proposed control can track the voltage and SOFC temperature references also in case of unexpected faults such as the air compressor fault and fuel leakage, which may result in both lifetime and performance improvement. In Ref. [16] a nonlinear model predictive control for SOFC stack was proposed to control the stack power, fuel utilization, and stack temperature. The controller utilizes a nonlinear lumped parameter model of the SOFC stack. Simulation results showed that the nonlinear predictive controller works satisfactorily following the power demand trajectory.

Most of the controllers proposed so far were designed only to control the stack whereas interactions between different components (e.g. between the SOFC stack and the burner, which preheats the incoming fuel, air, and water) were not taken into account. In real systems, all the components and their couplings should be taken into account. Moreover, most of the controllers proposed are quite complex and inappropriate for practical implementation. Besides, tuning procedure for most of the controllers was not included, which makes their implementation demanding.

The idea of this work is to propose a simple and efficient low-level control for SOFC power system without anode offgas recycle configuration. The control includes tuning procedure for the feedback controllers and as such could be easily implemented on a common programmable logic controller (PLC). The control is intended for the load following operation, whereas start-up and shut-down operation are not considered.

The paper is organized as follows. In Section The 2.5 kW SOFC power system, the model of a 2.5 kW SOFC power system, used for verification of the controllers, is described. In Section Feedforward-feedback control, the proposed feedforward-feedback control for the SOFC system is presented. In Section System electrical efficiency, the performance of the control is verified on the model of the SOFC