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Thermal stress management of a solid oxide fuel cell using neural network predictive control

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ABSTRACT

In SOFC (solid oxide fuel cell) systems operating at high temperatures, temperature fluctuation induces a thermal stress in the electrodes and electrolyte ceramics; therefore, the cell temperature distribution is recommended to be kept as constant as possible. In the present work, a mathematical model based on first principles is presented to avert such temperature fluctuations. The fuel cell running on ammonia is divided into five subsystems and factors such as mass/energy/momentum transfer, diffusion through porous media, electrochemical reactions, and polarization losses inside the subsystems are presented. Dynamic cell-tube temperature responses of the cell to step changes in conditions of the feed streams is investigated. The results of simulation indicate that the transient response of the SOFC is mainly influenced by the temperature dynamics. It is also shown that the inlet stream temperatures are associated with the highest long term start-up time (467 s) among other parameters in terms of step changes. In contrast the step change in fuel velocity has the lowest influence on the start-up time (about 190 s from initial steady state to the new steady state) among other parameters. A NNPC (neural network predictive controller) is then implemented for thermal stress management by controlling the cell tube temperature to avoid performance degradation by manipulating the temperature of the inlet air stream. The regulatory performance of the NNPC is compared with a PI (proportional–integral) controller. The performance of the control system confirms that NNPC is a non-linear-model-based strategy which can assure less oscillating control responses with shorter settling times in comparison to the PI controller.

1. Introduction

A great progress has been achieved on sustainable energy and environment protection in the last few years, however still more research and developments are needed to solve the energy issue and to reduce the emission, for reasonable standard of living for our world [1]. Among different types of small-scale power generation systems fuel cells have attracted considerable attention in the past two decades because of the worldwide need for more efficient and greener power generation systems [2]. SOFCs (solid oxide fuel cells) are considered as one of the most promising fuel cells for power generation due to their high efficiency, flexibility in the choice of fuel, need for less expensive catalysts, and a higher resistance to catalyst poisoning.

Most SOFCs are designed to function at high temperature thereby generating higher cell efficiencies in comparison to other kinds of fuel cells [3–7]. However, many research groups are working to reduce the operating temperature of SOFCs under 650 °C in order to reduce material degradation, prolong stack-lifetime and decrease stack material costs by availing common metal materials [8]. Therefore, it is of paramount importance to manage the stack temperature of a tubular SOFC in a proper manner [8]. Control of the SOFC temperature is significant in preventing damage to the fuel cell thereby maximizing the cell life and also improving its efficiency and performance.

Many of the related works in the literature is focussed on accurately predicting the thermal and other distributions in the cell through detailed mathematical modelling [9–13]. In experimental investigations on SOFC systems, the speed of load changes is chosen to be slow in order to prevent damage to the fuel cell. This needs to be performed because a control method that manages the fuel cell temperature variation and allows for variable load operation has not been established yet [14,15].

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SOFCs have challenging control issues due to their multi-time-scale dynamics, nonlinearity and tight operational constraints [16]. They are highly nonlinear due to which their controller design requires special attention [17,18]. The control challenge in a fuel cell system needs to achieve multi-level objectives. A fuel cell system should be controlled effectively to ensure that (1) the system has adequate supply of power in the presence of rapid variations in the external loads, (2) the system achieves high efficiency and (3) the SOFC sustains a long operating life [19].

Due to the complexity of nonlinear control problems it is essential to use various computational or approximate procedures to solve them. MPC (model predictive control) is a powerful methodology suited for such applications. Several well established MPC methods have been described in the literature [20–25] and can be adapted effectively for SOFC control procedures.

One method involves the application of a model predictive control based on a Takagi–Sugeno (T–S) fuzzy procedure [26]. T–S fuzzy model consists of "if-then" rules with fuzzy precursors that are consequently followed by mathematical functions. The role of system identification is to establish both the nonlinear parameters of the precursors and the linear parameters of the following rules. Compared with other fuzzy models, the T–S model requires less rules; each rule's background (along with the respective linear function) can express the input–output representation in a large range. In addition, the fuzzy repercussion employed in the model is quite simple to handle [27]. Predictive controller based on the Hammerstein model of a SOFC is another approach that can be employed to maintain the outlet voltage of a SOFC at a desired value by regulating the flow rate of an inlet natural gas stream [20]. The Hammerstein model includes a static nonlinear section followed by a series of dynamic linear divisions. The model describes the dependence of the cell outlet voltage on the inlet natural gas flow rate. Their simulation results show that the Hammerstein model predicts the nonlinear dynamics of the SOFC in a satisfactory manner [20]. A nonlinear predictive controller based on genetic optimization to keep the SOFC voltage and fuel utilization within the desired range has also been discussed in the literature [28]. The model involves a simple nonlinear procedure mainly representing the electrochemical process. The authors show that in the presence of a 13% load change, the closed-loop performance is satisfactory. Wang et al. [21] have developed a subspace-based data-driven predictive controller for a SOFC stack. The proposed approach can deal with systems without a complete on-line measurement of all output variables. Such controlled variables involve the stack voltage, fuel utilization, ratio of partial pressure of hydrogen to oxygen and the pressure difference between the anode and the cathode, for measuring the overall voltage of the SOFC. The manipulated variables include the molar flow rates of hydrogen and oxygen, whereas the current demand is considered as a disturbance. This model results in an overdue that challenges the SOFC's control system and results in slowing down its dynamic performance. Vijay et al. [29] have proposed a predictive controller based on a bond graph SOFC model. Manipulated inputs include the air and fuel inlet as well as the outlet flow rates. The control system achieves their objectives subject to constraints on the fuel utilization, air utilization, the cell operating temperature as well as the anodic and cathodic pressures. However, pseudo bond graphs cannot be readily linked with other energy domains, except by means of some impromptu elements that may not obey the rules of common bond graph elements [30]. Zhang et al. [25] have developed a nonlinear predictive controller for a planar SOFC with an objective to keep the power output, fuel utilization and operating temperature reasonably constant by manipulating the current density as well as the inlet fuel and air flow rates. The states of the model have been estimated using a moving horizon state estimator. However, the iteration optimization procedures are time consuming and expensive, thereby making the process quite impractical. A set of stochastic noise variations have artificially been added to the output model of the SOFC to validate the robustness of the moving horizon estimator. Sanandaji et al. [31] have also developed a model predictive controller based on a reduced version of a complex physical model of a SOFC stack, with the low-complexity model being specifically tailored for real-time optimization. The model reduction is based on a method that continuously blends multiple linear models according to a scheduling parameter.

Yang et al. [23] have showed that the modified T–S fuzzy model is sufficiently accurate to follow the temperature response of the fuel cell stack and can easily be utilized to design temperature control strategies. Inui et al. [32] have proposed the manipulation of the air utilization variable along with the inlet gas temperature of a planar SOFC to control the fuel cell temperature. A high performance feedback controller has been developed to manipulate the fuel cell air flow and inlet fuel cell air temperature to keep the electrode temperature at a constant value [33].

Recently, ANNs (artificial neural networks) have become a promising approach for modelling the complexities of highly nonlinear fuel cell systems [34–36]. However, control study is a missing issue in such work. In regard to optimization techniques for controllers it is noted that the ANN performs better than other techniques like response surface methodology or even the Taguchi method [36,37]. However, very few articles are available on the development of effective control strategies using artificial network predictive control [24]. A possible advantage of a neural network model over other methods in MPC is that its structure may be easier to develop. In particular, MPC algorithms based on neural models are recommended. It is because neural models have several advantages. They have excellent approximation abilities [38] and may be successfully used to approximate nonlinear behaviour of numerous technological processes [39]. Neural networks are trained using available data sets, for which no technological knowledge about the process is necessary. Moreover, unlike other common model types, neural networks usually have a small number of parameters and their structures are inherently simple. If neural models are used for MPC applications, it is not necessary to solve on-line sets of differential and algebraic equations, which may be difficult and may lead to numerical problems.

An artificial neural network (ANN) can be used as a feed-forward process for predicting process output parameters in combination with the MPC approach, which is designed for non-linear systems having a constant input variable. In the MPC process the complete system model is used to foresee the future system trajectory and the optimal control signal is therefore implicitly a function of the entire system model. Hence, MPC is not applicable to fixed-structure control issues. In contrast, regulators based on the neural network function estimator can be applied to optimal fixed-structure control by imposing the appropriate configuration on the procedure [40].

In this work, the objective is to control the SOFC temperature using a NNPC (neural network predictive controller) that manipulates the temperature of the inlet air stream. Temperature of the SOFC is usually controlled by varying the air flow to the cathode channels [32,33]. A detailed model of an NH_3 (ammonia)–SOFC is used for the controller design after validating this model with a hydrogen-fuelled SOFC.

The organization of this paper is as follows. Section 2 describes the SOFC dynamic model. Section 3 describes the cell-tube temperature control procedure using the NNPC approach. Section 4 presents and discusses the performances of the NNPC controller. Finally, concluding remarks are presented in Section 5.