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Control of Fuel Cell Power Systems

Principles, Modeling, Analysis, and Feedback Design

– Monograph –

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Preface

Fuel cell systems offer clean and efficient energy production and are currently under intensive development by several manufacturers for both stationary and mobile applications. The viability, efficiency, and robustness of the fuel cell technology depend on understanding, predicting, monitoring, and controlling the fuel cell system under a variety of environmental conditions and a wide operating range.

Many publications have discussed the importance and the need for a well-designed control system for fuel cell power plants. From discussions with control engineers and researchers in the area of fuel cell technology it became apparent that a comprehensive book with a control-oriented approach to modeling, analysis, and design was needed. The field is fast evolving and there is a lot of excitement but also a lot of commercial or confidentiality considerations that do not allow state-of-the-art results to be published.

In this book, we address this need by developing phenomenological models and applying model-based control techniques in polymer electrolyte membrane fuel cell systems. The book includes:

- An overview and comprehensive literature survey of polymer electrolyte membrane fuel cell systems, the underlying physical principles, the main control objectives, and the fundamental control difficulties.
- System-level dynamic models from physics-based component models using flow characteristics, point-mass inertia dynamics, lumped-volume manifold filling dynamics, time-evolving spatially homogeneous reactant pressure or concentration, and simple diffusion, transport, and heat equations.
- Formulation, in-depth analysis, and detailed control design for two critical control problems, namely, the control of the cathode oxygen supply for a high-pressure direct hydrogen Fuel Cell System (FCS) and control of the anode hydrogen supply from a natural gas Fuel Processor System (FPS).
- Multivariable controllers that address subsystem conflicts and constraints from sensor fidelity or actuator authority.

- Real-time observers for stack variables that may be hard to measure or augment existing stack sensors for redundancy in fault detection.
- Examples where control analysis not only can be used to develop robust controllers but also can help in making decisions on fuel cell system redesign for improved performance.
- More than 100 figures and illustrations.

This book is intended for researchers and students with basic control knowledge but who are novices in fuel cell technology. The simplicity of the models and the application of the control algorithms in concrete case studies should help practicing fuel cell engineers. Other scientists from electrochemistry, material sciences, and fluid dynamics who wish to become familiar with the control tools and methods may also benefit from the comprehensive coverage of the control design. Managers or entrepreneurs interested in accessing the challenges and opportunities in fuel cell automation technology may also find this book useful.

Book Overview

The development of a model of a dynamic fuel cell reactant supply subsystem that is suitable for control study is explained in Chapters 2 and 3. The model incorporates the transient behaviors that are important for integrated control design and analysis. Models of the auxiliary components, namely, a compressor, manifolds, an air cooler, and a humidifier, are presented in Chapter 2. Inertia dynamics along with nonlinear curve fitting of the compressor characteristic map are used to model the compressor. The manifold dynamic models are based on lumped-volume filling dynamics. Static models of the air cooler and air humidifier are developed using thermodynamics.

The fuel cell stack model in Chapter 3 is composed of four interacting submodels, namely, stack voltage, cathode flow, anode flow, and membrane hydration models. The stack voltage is calculated as a function of stack current, cell temperature, air pressure, oxygen and hydrogen partial pressures, and membrane humidity. The voltage function presented in Section 3.1 is based on the Nernst open circuit voltage, and activation, ohmic, and concentration losses. Flow equations, mass continuity, and electrochemical relations are used to create lumped-parameter dynamic models of the flow in the cathode and anode in Sections 3.2 and 3.3. Mass transport of water across the fuel cell membrane is calculated in the membrane hydration model in Section 3.4.

A perfect controller for air humidification and a simple proportional controller of the hydrogen supply valve are integrated into the model to allow us to focus on the analysis and control design of the air supply system. In Chapter 4, we perform a steady-state analysis of the model in order to determine the optimal value of the air flow setpoint, termed oxygen excess ratio, that results in the maximum system net power. The resulting value agrees with the fuel cell specification in the literature, and thus indirectly validates the accuracy of the model. Results from the simulation of the model with a static feedforward controller based on the optimal setpoint are presented in Section 4.3. The model predicts transient behavior similar to that reported in the literature.

The control design of the air supply system using model-based linear control techniques is presented in Chapter 5. The goal of the control problem is to effectively regulate the oxygen concentration in the cathode by quickly and accurately replenishing oxygen depleted during power generation. Several control configurations are studied and the advantages and disadvantages of each configuration are also explained. Additionally, the performance limitations of the controller due to measurement constraints are also illustrated. In Section 5.5.2, the results from an observability analysis suggest the use of stack voltage measurement in the feedback to improve the performance of the observer-based controller. The analogy between the fuel cell closed-loop current-to-voltage transfer function and an electrical impedance, discussed in Section 5.6, can be useful to researchers in the area of power electronics. Section 5.7 presents an analysis of the tradeoff between regulation of cathode oxygen and desired net power during transient. A range of frequencies associated with the tradeoff is determined.

In Chapters 6 and 7, a control problem of the partial oxidation based natural gas fuel processor is studied. The components and processes associated with the processor are explained in Section 6.1. A dynamic model of the processor is also presented in Chapter 6. Transient flow, pressure, and reactor temperature characteristics are included. The reaction products are determined based on the chemical reactions, and the effects of both the oxygen-to-carbon ratio and the reactor temperature on the conversion are included. The model is validated with a high-order detailed model of the fuel cell and fuel processor system, and the results are shown in Section 6.3.

A two-input two-output control problem of regulating the catalytic partial oxidation (CPOX) temperature and the stack anode hydrogen concentration using natural gas valve and air blower commands is studied in Chapter 7. Section 7.3 illustrates the use of the relative gain array method to find appropriate pairings of the system input and output and also to analyze the system interactions. The analysis shows that large system interactions degrade the performance of the decentralized controller, especially during transient operation. A model-based multivariable controller for the fuel processor system is designed in Section 7.5 using the linear quadratic optimal method. It is shown that significant improvement in CPOX temperature regulation can be achieved with the designed multivariable controller. The controller is then analyzed to determine the important terms that contribute to the improvement of the closed loop performance. This will be useful in the simplification and implementation of the controller. Chapter 8 provides a summary and contributions of the work. Several topics that need to be addressed and several other interesting areas to study are also given.

The major technical topics covered in this book are:

- Two control problems of the fuel cell power generation system are formulated. The first problem is the control of the air supply system for a high-pressure direct hydrogen fuel cell system (FCS). The objective is to control the compressor motor command to quickly and efficiently replenish the cathode oxygen depleted during system power generations. The second problem is the control of a low-pressure natural gas fuel processor system (FPS). The goal is to coordinate an air blower and a fuel valve in order to quickly replenish the hydrogen depleted in the fuel cell anode while maintaining the desired temperature of the catalytic partial oxidation reactor.
- Control-oriented dynamic models suitable for control design and analysis are created. The complexity of the models is kept minimal by considering only physical effects relevant to the control problems. The models are developed using physics-based principles allowing them to be used for different fuel cell systems requiring only parameter modifications. Moreover, the variables in the models represent real physical variables providing insight into the dynamic behavior of the real system. The causality of the process is clearly demonstrated in the models.
- The models are used in the model-based control analysis to develop controllers and to determine required control structures that provide an enhanced performance over conventional controllers. Moreover, the analysis provides insight into the performance limitations associated with plant architecture, sensor location, and actuator bandwidth.
  - For the FCS, the limitations of using integral control and an observer-based controller arise from sensor locations. In particular, a direct measurement of the performance variable (*i.e.*, the oxygen excess ratio) is not possible. The compressor flow rate, which is located upstream from the stack, is traditionally used as the only feedback to the controller. Our observability analysis shows that the stack voltage measurement can be used to enhance the closed-loop system performance and robustness. The voltage measurement is currently used only for safety monitoring. However, we demonstrate that the fuel cell stack mean voltage can be used for active control of fuel cell stack starvation. This result exemplifies the power of control-theoretic tools in defining critical and cost-effective sensor location for the FCS.
  - An additional limitation arises when the FCS architecture dictates that all auxiliary equipment is powered directly from the fuel cell with no secondary power sources. This plant configuration is preferred due to its simplicity, compactness, and low cost. We used linear optimal control design to identify the frequencies at which there is severe tradeoff between the transient system net power performance and the stack starvation control. The result can be used to determine the required size of additional energy or oxygen storage devices in the case where fast transient response is required. We demonstrated that the multi-

variable controller improves the performance of the FCS and results in a different current–voltage dynamic relationship that is captured by the closed-loop FCS impedance. We expect that the derived closed-loop FCS impedance will be very useful and will provide the basis for a systematic design of fuel cell electronic components.

- Multivariable feedback analysis using the control-oriented model of the FPS indicates large system interactions between the fuel and the air loops at high frequencies. Our analysis shows that the magnitude and speed of the fuel valve limit the closed-loop bandwidth in the fuel loop, and thus affect hydrogen starvation. We demonstrate that fast regulation of CPOX temperature, which is the objective in the air loop, requires a fast blower and air dynamics if a decentralized control structure is used. On the other hand, a slow blower can also accomplish similar performance if it is coordinated with the fuel valve command. The coordination is achieved with a model-based controller that decouples the two loops at the frequencies of high interaction. With this result we provide rigorous guidelines regarding actuator specifications and the necessary software complexity for multiple actuator coordination.

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