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Solid oxide fuel cell: Perspective of dynamic modeling and control☆

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ABSTRACT

This paper presents a review of state-of-the-art solid oxide fuel cell (SOFC), from perspective of dynamic modeling and model-based control. First, the historical and current status of SOFC development is overviewed. Then the main components of the SOFC along with their governing transport equations are discussed. These two sections provide fundamentals for understanding the SOFC. Following the sequence from power generation to energy losses within the SOFC, the section of dynamic modeling starts from an overview of energy generation, followed by discussion of energy losses and analysis of dynamics that affect energy generation and losses. This section of dynamic modeling is concluded by considering the model validation problem and other related challenging issues from the modeling perspective. Once SOFC dynamics are understood, the paper continues its journey to the SOFC control problem. This section starts from a general description of control problems in SOFC, continued with an overview of the existing control strategies and followed by a sample nonlinear MPC solution. The section is concluded by discussion of some of the challenges in SOFC control.

1. Introduction

Today's energy hungry civilization is in search of an alternative source to replace the currently available but continuously depleting energy sources. Stringent environmental regulations restricting emissions of green house gases, SOx, and NOx have narrowed down the search for a clean source of energy to a few options. It has generated a lot of attention towards the fuel cell as one of the alternative sources of clean energy. Fuel cells are electrochemical devices that directly convert chemical energy to electrical energy. Since it does not involve any rotary or thermal components, it does not suffer from any friction and combustion loss. Moreover, the unused fuel from the cell can be used to generate more power, contributing to its high overall efficiency.

Among various fuel cells, the low temperature proton exchange membrane fuel cell (PEM) and the high temperature solid oxide fuel cell (SOFC) have been identified as the likely fuel cell technologies that could capture the most significant fuel cell market in the future. This paper will focus on SOFC.

In order to control SOFC, it is necessary to understand its dynamic characteristics. Modeling and control are two integral parts of the advanced process control strategies which are intricately dependent on each other. From the view point of process control, the models should be easy to use for designing controllers and yet be detailed enough to give a sufficient account of the system dynamics.

With the advent of cheap computational power, a surge of application of previously non-implementable complex controllers such as the nonlinear model predictive controller has been seen in industries. In this paper, nonlinear MPC is used to demonstrate control application in the fuel cell system, based on the models developed from first principles.

Dynamic models can be used to investigate responses of fuel cells under various operating conditions. The pitfalls associated with the design and material selection could be revealed from the responses. By means of optimal control, one can steer the operating condition towards favorable one to improve durability and efficiency of fuel cells. A real-time monitoring system can safeguard fuel cell operations. Thus dynamic modeling, control and monitoring are the essential ingredients of fuel cell developments, and call for solutions that need active participation of the process control community.

This paper will review the state-of-the-art SOFC from perspective of operation principles, dynamic models, and control strategies, developed by the authors as well as other researchers, over the recent years. Some of the future challenges in the solid oxide fuel cell research will also be discussed.

2. State of the art

Alkaline fuel cell (AFC), proton exchange membrane fuel cell (PEM), direct methanol fuel cell (DMFC), phosphoric acid fuel cell

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