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A new two-stage design of feedback controllers for a hydrogen gas reformer

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ABSTRACT

In this paper we have first reviewed operations of a hydrogen gas reformer and provided its linearized mathematical model. Then, we have simplified an existing algorithm for a two-stage design of feedback controllers for linear continuous-time time-invariant systems. The proposed design significantly reduces the computational requirements and provides flexibility of designing different type of controllers for different dynamic parts of the system. Since the hydrogen gas reformer (also known as a fuel processing system) possesses slow and fast modes (state variables), the newly proposed design is further simplified and specialized for this class of systems. The obtained algorithm is efficiently applied with very high accuracy to the hydrogen gas reformer. As a matter of fact, the eigenvalue placement problem is solved for the reformer dynamics for both slow and fast modes. The design is so flexible that combined hybrid controllers (optimal, robust, set-point, eigenvalue assignment controllers or any other linear controller) can be designed independently for particular subsystems of the hydrogen gas reformer. The hybrid linear feedback controller design for the hydrogen gas reformer that optimizes its slow subsystem and assigns the desired eigenvalues to its fast subsystem is also presented in the paper.

Introduction

In this paper we present a new two-stage feedback controller design technique for a hydrogen gas reformer [1–6], which produces hydrogen from natural gas that is used for PEM (proton exchange membrane (also known as polymer electrolyte membrane)) fuel cells. Natural gas is a hydrocarbon gas mixture consisting mostly of methane (CH_4) with small amounts of paraffin (saturated hydrocarbon), carbondioxide, nitrogen, and hydrogen sulfide. To extract hydrogen from natural gas several simple reactions have to be performed as explained in Section Hydrogen gas reformer operation and modeling. The hydrogen obtained is pumped to the anode side of the PEM fuel cell [1–3].

Modeling and control of the hydrogen gas reformer dynamics has been an important and challenging research area, as discussed in Refs. [1,3,6] and references therein. The mathematical model of the hydrogen gas reformer considered in this paper is of a relatively high order (ten) and it has variables that operate in two-time scales [5], slow and fast, which requires additional attention due to potential numerical ill-conditioning (for example, huge slope at the initial time of the fast state variables and near-singularity of matrices involved in numerical computations). The two-time scale dynamics comes from different processes that govern

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dynamics of hydrogen gas reformer coupled to the PEM fuel cells. Such processes are chemical, electrical, electronic, electrochemical, mechanical, and thermodynamic, and they have different time constants that influence the hydrogen gas reformer and coupled fuel cell multi-time scale dynamics.

Importance of fuel cells as green electric energy generators has been nicely demonstrated in a recent book [7]. PEM fuel-cells are the most developed among all fuel-cells and they can be used for both mobile (vehicles, portable computing devices) and stationary applications (residential and industrial electric power generation and data centers). It is interesting to point out that Apple Inc. filled a patent on portable computing devices [8] that use fuel cells. Moreover, the efficient use of renewable energy sources such as fuel cells for Internet Protocol (IP) over Wavelength Division Multiplexing (WDM) fiber optic networks with data centers was considered in Ref. [9].

The paper is organized as follows. In Section Hydrogen gas reformer operation and modeling we review operations of the hydrogen gas reformer and its mathematical modeling and provide a linearized model. In Section New two-stage design of linear feedback controllers, a new two-stage design algorithm of linear feedback controllers is developed. The newly proposed design is further simplified and specialized for systems with slow and fast state variables (modes) in Section Two-stage linear feedback design for systems with slow and fast modes. In Section Two-stage linear feedback controllers for hydrogen gas reformed slow and fast dynamics, we first present dynamics of the hydrogen gas reformer in two-time scales that corresponds to its natural dynamics composed of slow and fast state variables, and then independently design appropriate slow and fast linear feedback controllers to assign desired eigenvalues to the slow and fast reformer dynamics. The design presented is so flexible that combined hybrid controllers (optimal, robust, set-point, eigenvalue assignment controllers or any other linear controller) can be designed independently for particular subsystems of the hydrogen gas reformer. The hybrid linear feedback controller design for the hydrogen gas reformer that optimizes its slow subsystem and assigns the desired eigenvalues to its fast subsystem is also presented in Section Two-stage linear feedback controllers for hydrogen gas reformed slow and fast dynamics. Simulation results obtained via the software package MATLAB are also presented. The simulation results obtain show agreement with the previously published simulation results for the same model of the hydrogen gas reformer.

Hydrogen gas reformer operation and modeling

Fuel cells utilize chemical reactions with hydrogen gas to produce electricity. However, H_2 gas is not always easily available for a fuel cell system. A solution to this problem is to use a hydrogen gas reformer also known as the Fuel Processor System (FPS) to purify gas, typically natural gas, into the needed H_2 gas, [1–6]. A common process used to extract hydrogen from natural gas in an FPS is partial oxidation. This process uses chemical reactions of natural gas and air to produce a H_2 rich gas product. The four main reactors of the FPS shown in Fig. 1 are:

Hydro-Desulfurizer (HDS), Catalytic Partial Oxidizer (CPOX), Water Gas Shift (WGS), and Preferential Oxidizer (PROX). Once the gas travels through all of these reactors, H_2 rich gas will be produced. In Fig. 1, HEX stands for a heat exchanger and MIX for a mixer.

Natural gas enters the FPS via a high pressure source, usually a tank or a gas line. The gas is first fed through the hydro-desulfurizer to eliminate any sulfur that could be contained in the gas. This is done because sulfur can poison the water gas shift. The desulfurized gas is then passed to the mixer (MIX), where it blends with air. The air is first brought into the FPS by a blower, and then passes through the heat exchanger to reach a necessary temperature.

Once mixed, the gas passes through the catalytic partial oxidizer where a catalyst causes the natural gas to react with the oxygen in the air. Two exothermal reactions take place in the CPOX.

(CPOX): Partial Oxidation (POX) and Total Oxidation (TOX)

Partial oxidation produces H_2 gas and carbon monoxide. The total oxidation produces water and carbondioxide. Even though, both reactions generate heat, TOX releases much larger amount of heat ($\Delta H^{o}_{tox} = -0.8026 \times 10^{6} J/mol$)

$$(POX) \quad CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2 \quad \Delta H^{o}_{pox} = -0.036 \times 10^{6} J/mol$$

$$(TOX) \quad CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \Delta H^{o}_{tox} = -0.8026 \times 10^{6} J/mol$$

Since only POX is producing H_2, it is preferable to increase the amount of gas reacting through POX instead of TOX. That is highly dependent on the ration of O_2 and gas entering CPOX and the CPOX catalyst bed temperature T_{cpox} [10]. In addition, very high temperature T_{cpox} can cause CPOX damage, while the low temperature T_{cpox} causes inefficient reactions. Since the reactions in the CPOX, especially H_2 production, are strongly dependent on the CPOX reactor temperature T_{cpox}, it is necessary to control the temperature efficiently.

Even though, H_2 is produced by the POX reaction, carbon monoxide is also produced. CO poisons the PEM fuel cell catalyst and therefore needs to be removed. This issue gives need for the next two reactors, the water gas shift and the preferential oxidizer. From the CPOX, the gas mixture flows into the water gas shift, where water is injected into the chamber to react with CO.

$$(WGS) \quad CO + H_2O \rightarrow CO_2 + H_2$$

The WGS reaction eliminates CO and produces additional H_2. This process does not convert all CO into CO_2, and the mixture is not safe for fuel cell application. Therefore, the gas mixture is next passed into the PROX, where the remaining CO reacts with the oxygen from the injected air.

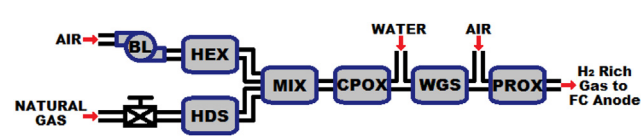

Fig. 1 – Fuel processor system.