398b Dynamics, Modeling and Control of Integrated Reformer-Fuel Cell Systems

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Fuel cells are chemical devices that convert the Gibbs energy of reaction of a fuel with an oxidant into electric power. A fuel cell consists of an electrolyte layer in contact with a porous anode and cathode on either side. In typical fuel cells, gaseous fuels are fed continuously to the anode and an oxidant is fed continuously to the cathode; the electrochemical reaction takes place at the electrodes to produce an electric current. The high power density and rapid adjustment to power demands make proton exchange membrane fuel cells (PEMFCs) one of the important candidates for use in stationary and transportation power applications.

Fuel cell plant design requires an appropriate integration of components, especially fuel processing units such as steam reformers. While the supply of hydrogen to the fuel cell anode may be achieved by supplying it from storage, using a reformer allows us to convert a more efficiently stored fuel (methanol or natural gas) into hydrogen. While automotive applications typically involve the use of on-board storage (thus decoupling the reformer from the fuel cell), stationary power applications involve the use of integrated reformer-fuel cell systems. These systems can range from micropower applications for small appliances to a few kilowatts for larger back-up power applications. The dynamics and time scales in the reformer are significantly different from those of the fuel cell, and the control of these systems is a non-trivial task. Varying demand requirements on the fuel cell create the need for rapid changes in the hydrogen output of the reformer, which are difficult to achieve without some kind of feedforward compensation. Also, changes in the reformer performance (output flow rate, composition or water content) act as disturbances to the fuel cell, which must be rejected by the regulatory controller.

However, there are not many instances of studies on the dynamics and control of integrated reformer-fuel cell systems in the literature. Pukrushpan et al. [1] study the effect of fuel cell dynamics on the air compressor, but do not consider the integration of a reformer with the fuel cell. El-sharkh et al. [2] construct a model of PEM fuel cell stack with a methanol reformer for residential applications, but they use a highly simplified fuel cell model that essentially consists of a (linearized) transfer function based representation of the dynamics.

In this work, we develop an integrated reformer-fuel cell model from first principles and highlight a few interesting aspects of the dynamics of the integrated system. We then develop appropriate controllers to accommodate the peculiarities of the system dynamics and provide simulation results on the control of the integrated system. We consider methanol and natural gas reformers, and compare the results for each of these cases. We also consider the effect of hydrogen purification applied to the reformate using pressure swing adsorption or CO conversion, before it is fed to the fuel cell.

The dynamic reformer model consists of a reforming and a water gas shift section, and uses a compartments-in-series model. Kinetics and energy effects of the reforming and water gas shift reactions are taken from the literature. Heat is supplied through a burner, and heat exchange with burner exhaust gases is taken into account. The dynamic effect of the balance of plant of the reformer is also included in the analysis.

The PEM fuel cell model is modified from the work of Golbert and Lewin [3], and captures spatial dependencies of voltage, current, flows and temperatures. The modifications include changes in the description of water transport through the membrane. The water flow is modeled taking into account condensation and evaporation, water drag through the membrane, and water generation by the reaction at the cathode. The controlling dynamic component of the model is the temperature, which varies slower than the other variables. The dynamical analysis allows characterization of the fuel cell polarization curves based on the time varying current, partial oxygen and hydrogen pressure, temperature, and membrane hydration. An important feature of the fuel cell model is that the gain (of power density to changes in cell voltage) changes sign in the operating region of interest. For integration with the reformer model, simple assumptions are made to extend the cell model to a stack model.

A nonlinear model predictive controller is designed to control the integrated reformer-fuel cell system. The control studies include setpoint-tracking studies, where the entire system tracks a varying electric load on the fuel cell, and disturbance rejection studies. The disturbances studied include fluctuations in the reformer feed, changes in reformer performance and reformate composition, disturbances in the airflow to the cathode (through a disturbance in the air compressor, for example), etc. We also present results on system start-up performance.

References:

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