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Quasi-min-max fuzzy model predictive control of direct methanol fuel cells

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Abstract

Direct methanol fuel cells (DMFCs) are known as a promising power source in future. In this paper, we consider steering a DMFC plant to a desired operating point while optimizing the transient performance according to a quadratic cost function. Quasi-min-max fuzzy model predictive control (FMPC) with input constraints is proposed for the DMFC. In order to reduce the computational burden for real time implementation, a partial off-line quasi-min-max FMPC is also proposed. In this case, a bank of invariant sets together with the corresponding feedback control laws are obtained by solving some linear matrix inequalities (LMIs) off-line, leaving the online part a bisection search and a much simplified constrained optimization problem. Online computation complexity for both the quasi-min-max FMPC and the partial off-line one is also analyzed. Simulation results are given to show the effectiveness of the proposed controllers.

Keywords: Fuzzy control; Model predictive control; Off-line computation; DMFC

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1. Introduction

Fuel cells are devices which can convert chemical energy into electrical energy directly. They have great potential applications because of high efficiency and low emission. Direct methanol fuel cells (DMFCs) are one of the newest fuel cells. DMFCs use methanol as the fuel directly and thus have high energy density [6]. DMFCs are supposed to work in portable electrical devices such as mobile phones, laptops and even some military applications. Therefore, in the past decade, they have attracted considerable attention. In order to have a better understanding of DMFCs, the first-principle modeling work has been done. In [2], the authors developed a steady state, isothermal model of a DMFC. In [1], an one-dimensional dynamic DMFC model was studied. The authors considered both the chemical reaction mechanism and mass transportation. Some other works studied the two-dimensional dynamic models of DMFCs, such as [3] and [4]. A more detailed discussion on the DMFC modeling can be found in a review paper [5].

A DMFC is often considered to work with a battery or a super capacitor, which can keep its output voltage at a certain value. In this condition, given a load current, there are some desired operating points for the DMFC system,

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such as the maximal power point (MPP) or maximal efficiency point (MEP). In this paper, we consider steering the DMFC system to a desired operating point. At the same time, its transient performance is optimized. The transient operation of the DMFC plays an important role in issues of safety and cost. In addition, for the long term operation it is desirable for the system to be stabilized at the desired operating point. Otherwise, severe methanol crossover or shortage of fuel could happen, which will cause waste of fuel or insufficient power supply.

In this paper, the DMFC control problem is studied in the framework of fuzzy model predictive control. Model predictive control (MPC), also known as receding horizon control (RHC) is often applied in chemical processes since it can effectively deal with both state and input constraints [10]. It is noticed that the first-principle models of DMFCs usually have high nonlinearity, which makes it difficult to synthesize a control law. We consider representing the nonlinear system using a fuzzy model, which can approximate a nonlinear plant to any degree of precision [9]. There are peer works considering fuzzy model predictive control (FMPC), such as [14,17,18] and [24]. Most papers studying FMPC adopted the min-max approach, which was first introduced in [19] for linear parameter varying (LPV) systems. In the min-max approach, a state feedback controller is applied to the system, the gain of which is obtained by online solving a constrained optimization problem. In [16], the authors introduced the so-called "quasi-min-max" MPC for LPV systems. They assumed that system model was available at each time instant, but unknown for the future. The system input at each step was a free decision variable to the problem of minimizing an upper bound of the "quasi-worst-case" cost. The author of [15] extended the work to fuzzy systems and used the piecewise Lyapunov function (PLF). The control approach of quasi-min-max is also adopted here. Different from [15], the fuzzy Lyapunov function is utilized in this paper, which is a smooth function rather than the piecewise one. To make it more practical for the DMFC control, a partial off-line realization of the quasi-min-max FMPC is also proposed, which is another contribution of this paper. In the partial off-line scheme, the online computation is significantly simplified. Moreover, a detailed discussion of the closed-loop stability and feasibility of the online optimization problem is given in this paper.

The rest of the paper is organized as follows. In Section 2, the physicochemical model of the considered DMFC is introduced firstly, and the fuzzy model is then given. Section 3 studies both quasi-min-max FMPC and a partial off-line scheme. The computation complexity issue is also discussed. Simulation results are given in Section 4. Finally, the paper concludes with some remarks and possible future extensions.

2. DMFC system description and T–S fuzzy model representation

2.1. System description

This paper considers a direct methanol fuel cell model introduced in [11]. Under the assumption that the temperature is constant and the air at the cathode side is sufficient, balance equations for methanol concentration in the anode catalyst layer $c^{\mathrm{AC}}_{\mathrm{CH_3OH}}$, carbon-doped oxide surface coverage $\theta_{\mathrm{CO_X}}$, anode overpotential η_{A}, and cathode overpotential η_{C} can be formulated as the following time-dependent ordinary differential equations,

$$\frac{\mathrm{d}c^{\mathrm{AC}}_{\mathrm{CH_3OH}}}{\mathrm{d}t} = \frac{k^{\mathrm{AD}}A_{\mathrm{S}}}{V^{\mathrm{AC}}}\left(c^{\mathrm{F}}_{\mathrm{in}} - c^{\mathrm{AC}}_{\mathrm{CH_3OH}}\right) - \frac{A_{\mathrm{S}}}{V^{\mathrm{AC}}}n^{\mathrm{M}}_{\mathrm{CH_3OH}} - \frac{A_{\mathrm{S}}}{V^{\mathrm{AC}}}r_{A1}, \tag{1}$$

$$\frac{\mathrm{d}\theta_{\mathrm{CO_X}}}{\mathrm{d}t} = \frac{1}{c_{\mathrm{max,Pt}}}(r_{\mathrm{A1}} - r_{\mathrm{A2}}), \tag{2}$$

$$\frac{\mathrm{d}\eta_{\mathrm{A}}}{\mathrm{d}t} = \frac{1}{C^{\mathrm{AC}}}i_{\mathrm{cell}} + \frac{1}{C^{\mathrm{AC}}}(-4Fr_{\mathrm{A1}} - 2Fr_{\mathrm{A2}}), \tag{3}$$

$$\frac{\mathrm{d}\eta_{\mathrm{C}}}{\mathrm{d}t} = -\frac{1}{C^{\mathrm{CC}}}\left(i_{\mathrm{cell}} - 6Fr_{\mathrm{C}} - 6Fn^{\mathrm{M}}_{\mathrm{CH_3OH}}\right), \tag{4}$$

where

$$r_{\mathrm{A1}} = r_{\mathrm{A10}}\frac{C^{\mathrm{AC}}_{\mathrm{CH_3OH}}}{C^{\mathrm{ref}}_{\mathrm{CH_3OH}}}\frac{1-\theta_{\mathrm{CO_X}}}{1-\theta^{\mathrm{ref}}_{\mathrm{CO_X}}}\exp\left[\frac{\alpha_{\mathrm{A1}}F}{RT}\eta_{\mathrm{A}}\right],$$

$$r_{\mathrm{A2}} = r_{\mathrm{A20}}\frac{\theta_{\mathrm{CO_X}}}{\theta^{\mathrm{ref}}_{\mathrm{CO_X}}}\exp\left[\frac{\alpha_{\mathrm{A2}}F}{RT}\eta_{\mathrm{C}}\right],$$