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Multiple model predictive control for a hybrid proton exchange membrane fuel cell system

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ABSTRACT

This paper presents a hierarchical predictive control strategy to optimize both power utilization and oxygen control simultaneously for a hybrid proton exchange membrane fuel cell/ultracapacitor system. The control employs fuzzy clustering-based modeling, constrained model predictive control, and adaptive switching among multiple models. The strategy has three major advantages. First, by employing multiple piecewise linear models of the nonlinear system, we are able to use linear models in the model predictive control, which significantly simplifies implementation and can handle multiple constraints. Second, the control algorithm is able to perform global optimization for both the power allocation and oxygen control. As a result, we can achieve the optimization from the entire system viewpoint, and a good tradeoff between transient performance of the fuel cell and the ultracapacitor can be obtained. Third, models of the hybrid system are identified using real-world data from the hybrid fuel cell system, and models are updated online. Therefore, the modeling mismatch is minimized and high control accuracy is achieved. Study results demonstrate that the control strategy is able to appropriately split power between fuel cell and ultracapacitor, avoid oxygen starvation, and so enhance the transient performance and extend the operating life of the hybrid system.

1. Introduction

Proton exchange membrane (PEM) fuel cells are clean and highly efficient electrochemical devices that convert hydrogen directly into electricity. They have been considered as alternative power sources for vehicles, mobile robots, backup power sources, etc. In practical applications, PEM fuel cells are usually arranged with auxiliary power sources, such as batteries and ultracapacitors, to form hybrid systems.

The electric loads supplied by a hybrid fuel cell system may frequently fluctuate. Abrupt changes in power may cause oxygen starvation in the fuel cell, may overcharge or overdischarge the ultracapacitor, and may reduce the working life of the system in a long term [1,2]. Therefore, sophisticated power management and oxygen control are necessary.

Many studies have been carried out on power management. Jiang et al. [3] present an adaptive control strategy that adjusts the output current set point of the fuel cell. Ferreira et al. [4] studied a fuzzy logic supervisory-based power management strategy for a fuel cell/ultracapacitor/battery combined electric vehicle. Guezennec et al. [5] and Rodatz et al. [6] designed an optimal control strategy to minimize the hydrogen consumption in a hybrid fuel cell system. Zhang et al. [7] proposed a wavelet-transform algorithm to identify and allocate power demands with different frequency contents to corresponding sources to achieve an optimal power management control algorithm.

In the aspect of oxygen control, Pukrushpan et al. [8,9] developed a mechanistic model suitable for the study of controls in fuel cell systems. Vahidi et al. [1,10] used a theoretical model-based predictive control approach to manage current and oxygen so as to avoid oxygen starvation and surge or choking of the air compressor in a fuel cell/ultracapacitor hybrid system. To enforce constraints on the oxygen supply and protect the fuel cells from oxygen starvation, Sun and Kolmanovsky [11] use a robust load governor to regulate the current drawn from the fuel cell. These strategies have all proved effective in avoiding oxygen starvation.

Model predictive control (MPC) works in a centralized manner for constrained control problems through a multivariable minimization [12]. A key advantage of MPC over other control schemes is the ability to deal with constraints in a systematic and straightforward manner [13]. Multiple model adaptive control has been widely utilized in improving the transient response of systems with boundary condition changes [14].

We have noticed that power management and oxygen control are typically investigated separately. That is to say, power distribu-

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tion command is determined first according to load requirement but without interacting with real-time fuel cell control, and then fuel cell system control (in which including oxygen supply control) is determined to respond to the power command signal while not to the load requirement directly. As a result, the hybrid system control is not global optimized. Our purpose in this paper, then, is to describe a centralized multiple models-based predictive control scheme that addresses both power distribution and oxygen control, and that can provide a systematic and globally optimized solution under multiple constraints.

The proposed control scheme is designed and implemented as follows. First, characteristics of the hybrid system over its whole operating range are identified and expressed as multiple linear discrete-time models by employing the fuzzy clustering technology. Each model corresponds to a typical operating zone of the hybrid system, and the models are updated online to cater for parameter variations of the real system. Second, constrained MPCs are designed for each model. Finally, an upper-layer adaptive switch is designed to determine the most appropriate model and to switch the corresponding MPC as needed. The control scheme is aimed to enhance the performance of the system, and to protect the hybrid system not only by avoiding oxygen starvation, but also by trading off transient demands between the fuel cell and the ultracapacitor, according to constraints and weighting matrices of the output errors.

The paper is organized as follows. In Section 2, structure and description of the predictive control using multiple models are introduced. Section 3 describes dynamic modeling of the hybrid system. Controllers are designed in Section 4. In Section 5, we implement and discuss experiment and simulation results. Conclusions are given in Section 6.

2. System structure and description

We focus on control of electric power and of the oxygen supply. We assume that the hydrogen is supplied at constant and appropriate pressure, humidity, and temperature, and that wave effects are insignificant. These assumptions should not undermine the validity of our work because pressure, temperature and humidity dynamics are much slower than the fuel cell power dynamics which we study in this paper [1].

2.1. System description

The hybrid fuel cell system studied in this paper, as shown in Fig. 1, is designed for an automobile application. The electrical outputs of two PEM fuel cell stacks are directly connected in parallel to the propulsion motor load. An ultracapacitor bank is also connected to the load through a bi-directional DC/DC converter to form a hybrid PEM fuel cell/ultracapacitor system. The ultracapacitor bank should supply peak power and should be recharged by the fuel cell. The hybrid system can be quite efficient because the fuel cell directly supplies the bulk of the load demand while the DC/DC converter only operates to meet transient demands.

The distribution of power between the fuel cell and the ultracapacitor depends on the duty ratio of the DC/DC converter, while the oxygen supply to the PEM fuel cell is regulated by the voltage applied to the air compressor, V_{cm}. Duty ratio of a DC/DC converter is defined as the ratio of switch on time interval, T_{ON}, to switching period T, i.e.

$$d = \frac{T_{ON}}{T}. \tag{1}$$

There exist two duty ratios in the bi-directional DC/DC converter. One duty ratio, d_c, is for charging the ultracapacitor, and the other, d_d, is for discharging the ultracapacitor.

Oxygen excess ratio is defined as

$$\lambda_{O_2} = \frac{W_{O_2,in}}{W_{O_2,rct}}, \tag{2}$$

where $W_{O_2,in}$ is the flow of oxygen into the fuel cell and $W_{O_2,rct}$ is the mass of oxygen reacted in the fuel cell and is related to the current drawn from the fuel cell.

The state of charge is usually defined as the ratio of energy stored in the ultracapacitor to the rated energy capacity of the ultracapacitor [15], i.e.

$$\overline{SOC} = \frac{V_c^2}{V_{c,max}^2}, \tag{3}$$

where V_c and $V_{c,max}$ are the instantaneous voltage and maximum voltage of the ultracapacitor, respectively. $V_{c,max}$ is constant and controlling $\overline{SOC}$ is equivalent to controlling $V_c/V_{c,max}$. As a result, we define a new state of charge, SOC, which is easier to control [1], i.e.

$$SOC = \frac{V_c}{V_{c,\max}}. \tag{4}$$

2.2. Control structure and principle

The framework of the multiple model predictive control is presented in Fig. 2. It has four major blocks, namely model predictive controllers, models, adaptive switch, and the controlled system.

There are n linear models and corresponding MPCs in the system. Namely, $Model_i$ ($i = 1, 2, \ldots, n$) is the ith linear model of the hybrid system at a typical operating zone and MPC_i is a model predictive controller designed for $Model_i$. $Model_{online}$ denotes the unit that updates each model online according to real-time data so as to cater for time variation of the system.

The adaptive switch, also called an upper-layer controller, is a decision unit that determines the most appropriate MPC to control the hybrid system during each control period. Briefly, its operating principle is as follows. Firstly, control signals are fed into the hybrid system and into each model simultaneously. Secondly, the output of each model is compared to the actual output, respectively. Finally, according to the errors, the adaptive switch periodically chooses the model that best matches the observed performance and then switches on the corresponding MPC. At each period, only one MPC is in service and occupies computational resources.

The system design consists of two major steps: identification of the hybrid system and design of the control. System identification consists of collecting input and output data from the hybrid system and dividing it into several sets based on fuzzy clustering. Then models are identified from each data set. Control design entails design of the MPCs and design of the adaptive switch. In designing the MPCs, we will focus on handling multiple constraints and enhancing computational speed. In design of the adaptive switch, it is important to design performance evaluation function and the switch mechanism.

3. Modeling of the hybrid system

The hybrid system is a multiple input and multiple output nonlinear system. This section establishes the bank of linear models that describe the hybrid system. Input and output data are divided into multiple sets through fuzzy clustering firstly and then the model for each data set is identified. In addition, the models will be updated online during utilization phase.