

Closed Loop Control Algorithm of Fuel Cell Output Power for a City Bus

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ABSTRACT

This paper studies a control algorithm for fuel cell/battery city buses. The output power of the fuel cell is controlled by a D.C. converter, and the output ports of the converter and the battery are connected in parallel to supply power for the electric motor. One way to prolong service life is to have the fuel cell system to deliver a steady-state power. However, because of fluctuations in the bus voltage and uncertainty in the D.C. converter, the output power of the fuel cell system changes drastically. A closed-loop control algorithm is necessary to eliminate the errors between the output and target power of the fuel cell system. The algorithm is composed of two parts, the feed forward one and the feedback one. Influences of the bus voltage and D.C. efficiency are compensated automatically in the feedback algorithm by using a PI algorithm. The stability and robustness of the algorithm is analyzed. Formulas for choosing suitable parameters are given considering both the transient process and the system stability. Experimental results show that, the stable relative error between the target power and the actual output power of the fuel cell system converges to zero. Because of signal noises introduced in the measurements of the current and the voltage, there are some noises in the actual output power. The average relative error (absolute value) during the measuring processes with the closed loop algorithm reduced to 1/3 of the level with the open loop algorithm, 1.5% and 4.5%, respectively. Based on the closed loop control algorithm proposed in this paper, a multi-objective optimal energy management strategy considering both of the fuel economy and system durability can be studied in the future.

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INTRODUCTION

Proton exchange membrane fuel cells (PEMFC) are favored in vehicle applications, because of the following advantages.

1) High efficiency: The energy efficiency for a fuel cell system can reach 45%~60%, 2~3 times of that of the ICE (internal combustion engine); 2) Zero emission: The outcome of the electro-chemical reaction in the fuel cell system is pure water; 3) Quiet working: No mechanical movements exist in the fuel cell stack, so it is less complex than mechanical systems and lower in noise emissions [1].

The first fuel cell bus (FCB) was launched by Ballard Power Systems, Inc. in 1993 with a 92kW PEMFC. After that, governments and transnational automotive

manufacturers set off a renaissance in research and demonstration of FCBs [2].

PEMFC have been developing very rapidly during the past five years, both in durability and system costs. The longest working life time of the PEMFC reaches 7000h, reported by UTC and AC Transit in US. The system cost has been reduced from 275 \$.kW⁻¹ in 2002 to 73 \$.kW⁻¹ in 2010. The target of DOE for the cost is 30 \$.kW⁻¹ in 2015, which is equivalent to gasoline engines [3].

China started FCB projects in 2002. Four generations have been developed since then. In these FCBs, the PEMFC is hybrid with a battery system. The fuel cell provides steady-state power, and the battery fulfills the dynamic power requirement, and recycles brake energy during sliding or



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braking processes. The durability of the fuel cell system is still a challenging problem, especially for China [2].

For such a hybrid fuel cell power-train, determining how to split power between the two power sources is a challenging problem. Not only the fuel consumption needs to be reduced [4, 5], but also the durability of the fuel cell system should be prolonged [6,7] while maintaining power output ability [8,9]. Dr. Thounthong P et al. proposed an energy management strategy for a fuel cell/ battery/ super capacitor hybrid power-train. A control strategy with three voltage control loops is proposed and verified. The super capacitor functions as a high power density component, the battery functions as a high energy density component, and the fuel cell works as a small dynamic source to prolong the working life time [10]. Zhang X et al studied a wavelet based algorithm to decouple power signals into different components, and split power between three power sources, a fuel cell system, a battery and a super capacitor [11]. Some other technologies based on modern control theory, e.g. intelligent control [12], sliding mode control [13,14], are also applied to split power between a fuel cell and other power sources.

There is a common viewpoint in these papers: it is preferred to deliver a steady-state power for the PEMFC to prolong its working life time. However, because of fluctuations in bus voltage and uncertainty in the D.C. converter, the output power of the fuel cell system changes drastically. A feedback algorithm is strongly required to eliminate the difference between the target and actual output power of the PEMFC automatically. This paper describes such an algorithm. The structure of the fuel cell/battery power-train is introduced. The control algorithm composed of feed forward and feedback parts are described. The stability and robustness of the algorithm is analyzed. An experiment was set up to verify the algorithm. The results of the experiment and conclusions are given.

FUEL CELL / BATTERY HYBRID POWERTRAIN

System Structure

Figure 1 (a) illustrates an FCB. Figure 1 (b) shows the structure of the PEMFC/battery hybrid power-train for the city bus. The output power of the fuel cell system is controlled by a buck D.C. converter.

The power-train is regulated by a networked control system. A time-triggered controller area network (TTCAN) protocol is designed [15]. Taking the VCU (Vehicle Controller Unit) as the center, such a networked control system can also be called a master-slave system [16].

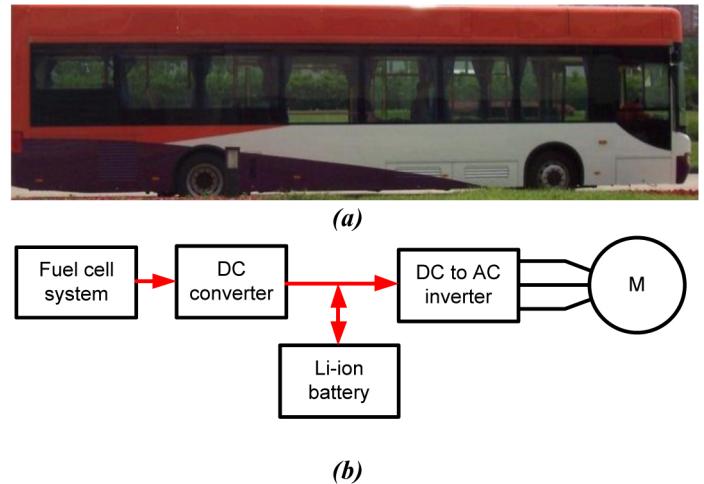


Figure 1. (a) An example of a fuel cell city bus (b) Fuel cell / battery power-train for the city bus

Performance of the Hybrid Power-train with Current Control Algorithm

The output power of the fuel cell system is calculated as follows.

$$P_{fcnet} = \frac{I_{dc}V_{dc}}{\eta_{dc}} \quad (1)$$

where P_{fcnet} is the net output power of the PEMFC, I_{dc} is the output current of the D.C. converter, V_{dc} is the output voltage of the D.C. converter, η_{dc} is the D.C. efficiency. The target D.C. current of the converter is calculated in a vehicle controller unit, and the output current of the D.C. converter is controlled in accordance with the target value. The net output power of the PEMFC is influenced by the D.C. voltage V_{dc} and the efficiency η_{dc} .

Figures 2 (a) - (c) present the performance of the FCB without a feedback control algorithm on a test bench with the "China city bus typical cycle".

Figure 2 (a) illustrates the output power of the fuel cell system and the electric motor. The peak power of the electric motor is around 175kW. The output power of the fuel cell system changes between 34 and 44kW. When the power requirement of the electric motor increases drastically, both of the PEMFC and the battery deliver an increasing power, causing the output voltage of the battery decreases, as shown in Figure 2 (b). Moreover, there is always uncertainty of the D.C. efficiency in the dynamic process. This will result in errors while calculating the target current. Shown as in Figure 2 (c), the absolute error is around 5% when $P_{dc} > 20kW$.

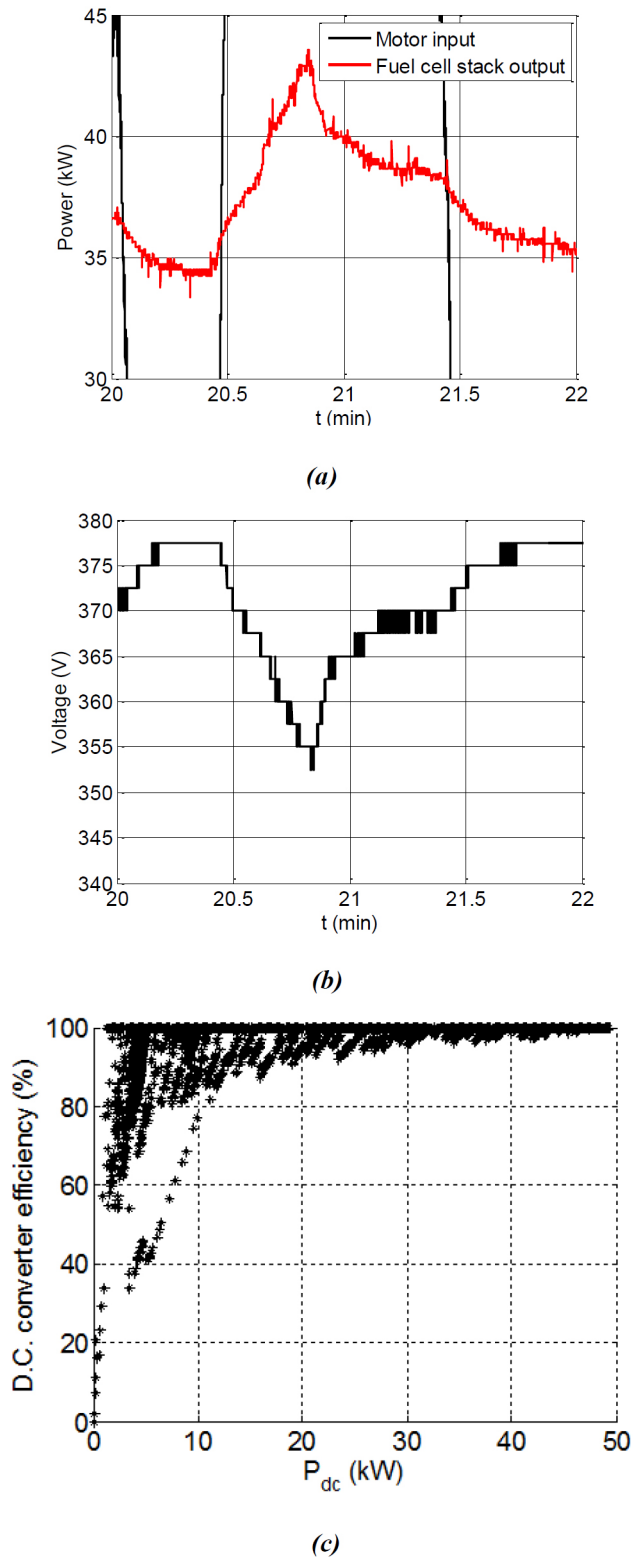


Figure 2. Performance of FCB without a feedback control algorithm (a) output power of the PEMFC and the electric motor (b) fluctuation of the bus voltage (c) uncertainty of the efficiency of the D.C. converter

CLOSED LOOP CONTROL ALGORITHM

A closed loop control algorithm is designed to eliminate the influences of the bus voltage and D.C. efficiency on the net output fuel cell power. It is composed of two parts, a feed forward part, and a feedback part.

Feed Forward Algorithm

In this algorithm, the target D.C. converter current $I_{dc,tg}$ is calculated as follows [17].

$$I_{dc,tg} = \frac{P_{fcnet,tg} \eta_{dc,avg}}{\bar{V}_{dc}} \quad (2)$$

where $P_{fcnet,tg}$ is the target net output power of the PEMFC, $\bar{V}_{dc}$ is the measured output voltage of the D.C. converter, $\eta_{dc,avg}$ is the average D.C. efficiency.

Feedback Algorithm

In this algorithm, a small increment of D.C. current $\Delta I_{dc,tg}$ is calculated using PI algorithm in accordance with the difference between target and actual power of the fuel cell system $\Delta P_{fcnet} = P_{fcnet,tg} - P_{fcnet}$.

$$\Delta I_{dc,tg} = K_p \Delta P_{fcnet} + K_i \int_0^t \Delta P_{fcnet} dt \quad (3)$$

where $K_p > 0$ $K_i > 0$ are parameters for the PI algorithm. These two parameters are not constants, but change with target power.

$$\begin{cases} K_p = f_p(\Delta P_{fcnet}) \\ K_i = f_i(\Delta P_{fcnet}) \end{cases} \quad (4)$$

Stability and Robustness Analysis

The control algorithm scheme can be described as in Figure 3, assuming the output current can be accurately controlled. K_1 is the feed forward parameter, K_2 is the physical system parameter, as in equation (5).

$$\begin{cases} K_1 = \frac{\eta_{dc,avg}}{\bar{V}_{dc}} \\ K_2 = \frac{\bar{V}_{dc}}{\eta_{dc}} \end{cases} \quad (5)$$

where $\bar{V}_{dc}$ is the measured output voltage of the D.C. converter, $\eta_{dc,avg}$ is the average D.C. efficiency, $\bar{V}_{dc}$ is the actual output voltage, and η_{dc} is the actual D.C. efficiency.

The transfer function between ΔP_{fcnet} and $P_{fcnet,tg}$ can be deduced based on this diagram.