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Design and control of a PEMFC powered electric wheelchair

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ARTICLE INFO

Article history:
Received 22 February 2012
Received in revised form
23 April 2012
Accepted 30 April 2012
Available online 8 June 2012

Keywords:
PEMFC
Electric wheelchair
Robust control
Battery
System integration

ABSTRACT

This paper proposes the design and control of a fuel-cell powered wheelchair. Electric wheelchairs can improve moving ability for people with walking problems. However, their traveling distances are limited by the capacity of their batteries. We designed a fuel-cell powered electric wheelchair that can be continuously operated, thereby extending the moving range. The system consisted of three subsystems: a commercial electric wheelchair, a proton exchange membrane fuel cell (PEMFC), and two secondary battery sets. The study was carried out in three parts, investigating the fuel-cell control, power management, and system integration. First, we designed multivariable robust controllers for a 500 W PEMFC system to charge the battery sets by constant voltage/current. Second, we designed a serial power management system, where the wheelchair motors were directly driven by the secondary battery sets, which in turn were charged by the PEMFC when their capacities dropped below a certain level. Lastly, we integrated the three subsystems and verified the system performance by experiments. The results confirmed the effectiveness of the PEMFC system as a way to extend the traveling distance of a motorized wheelchair.

1. Introduction

Electric vehicles that use various energy sources are viewed as devices that could mitigate the air pollution and global warming problems caused by fossil-fuel vehicles [1]. The development of gasoline-powered hybrid electric vehicles (HEV) and plug-in hybrid electric vehicles (PHEV) is now drawing social attention to this potential [2]. Different alternative fuels including natural gas, methanol, ethanol, hydrogen, and solar are now being considered as energy sources for generating electricity for vehicles [3]. Among these, hydrogen fuel cells are viewed as superior, especially for long-range travel [2,4–6] and many applications of fuel-cells have been reported for various types of vehicles [7–10] However, the application of fuel cells to medical devices such as wheelchairs is still limited [11].

In this study, we propose a fuel-cell powered electric wheelchair. Wheelchairs were developed to help people with walking disabilities, but the original wheelchairs operated on human power. The introduction of electric wheelchairs has improved patients' moving ability but the traveling range of these wheelchairs is limited by the capacity of their batteries. Therefore, in this paper, we introduced an electric wheelchair that uses a proton exchange membrane fuel cell (PEMFC) as a way to extend the user's moving distance.

The PEMFC has many advantageous properties, including low operating temperature, high efficiency, and low pollution, which make it an important alternative energy source. Forrai et al. [12] obtained the dynamic characteristics of PEMFC systems by viewing the PEMFC system as a circuit consisting of inner resistors and a capacitor. Gorgun [13] constructed a model that included water phenomena, electro-osmotic drag and diffusion, and a voltage ancillary. Woo and Benziger [14] improved system stability and performance by designing a proportional-integral-derivative (PID) controller to regulate the hydrogen flow rate. Vega-Leal et al. [15] controlled the PEMFC current output by regulating the air flow rate and temperature, and optimized the net power by tuning the

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0360-3199/$ – see front matter
doi:10.1016/j.ijhydene.2012.04.156

hydrogen flow rate. Wang et al. [16–19] developed a multi-input multi-output (MIMO) system and designed robust controllers that could provide steady voltage and reduce hydrogen consumption by regulation of the oxygen and hydrogen flow rates.

We constructed our PEMFC-powered wheelchair in three steps, focusing on fuel-cell control, power management, and system integration. First, we designed multivariable robust controllers to control the hydrogen and air flow rates of the PEMFC, in order to provide a steady voltage or current that would directly charge the battery sets without the need for DC/DC converters (this improves both system cost and efficiency). Second, we built a serial powertrain, where the PEMFC charges two $LiFePO_4$ battery sets by constant voltage or current, and these battery sets then directly drive the wheelchair motors. Lastly, the systems were integrated for experimental verification. The results confirmed the effectiveness of the proposed system as a way to extend the traveling range of a motorized wheelchair.

This paper is organized as follows: Section 2 introduces the subsystems, which include an electric wheelchair, a 500 W self-humidified PEMFC system, and the secondary battery sets. Section 3 designs H_∞ robust controllers for the PEMFC. Section 4 constructs a serial powertrain for the system. Section 5 integrates these subsystems for experimental verification. Lastly, we draw conclusions in Section 6.

2. Model description

The proposed PEMFC wheelchair is shown in Fig. 1. It consists of three subsystems: an electric wheelchair, a 500 W PEMFC, and two secondary battery sets. The specifications of the wheelchair are illustrated in Table 1 [20]. Because the rating power and the maximum power of the wheelchair are 100–180 W and 300 W, respectively, we selected a 500 W PEMFC as the main power source of the system.

The PEMFC subsystem, shown in Fig. 2, is composed of a stack, a passive humidifier, an air pump, a proportional hydrogen valve, and cooling fans. The passive humidifier provides humidity for the air and hydrogen inputs, to improve system performance. The hydrogen valve regulates the hydrogen flow rate into the anode, while the air pump controls the air flow rate into the cathode. The purge valve is operated in a dead-end model; i.e., the hydrogen outlet is closed except for purging, to maintain the necessary reactant within the system. During experiments, the valve is purged for 1 s at intervals of 100 s. The specifications of the stack are illustrated in Table 2 [21,22].

Table 1 – Specifications of the wheel-chair.

Model: THE LIN™ MDS 203 [20]	
Maximum speed	6.4 km/h
Turning radius	58 cm
Ground clearance	12 cm
Motor voltage	DC 24 V
Gradient	12° (250 lb)
Caster	8" PU tire
Drive wheel	12.5" foam filled tire
Power	100–180 W

We designed a series powertrain for the system, because the wheelchair motors were operated at 24 V with a rating power of 100–180 W, which was much less than the power of the PEMFC system. We constructed the secondary battery sets using A123™ $LiFePO_4$ cells [23] because of their advantageous properties (i.e., high energy density, high power density, and safety). The specifications of the secondary battery sets are illustrated in Table 3. Each battery set consisted of twenty-one cells (seven in series and three in parallel) that provided 23.1 V and 6.9 A h for the system.

3. Identification and control of the PEMFC system

From the system point of view, a PEMFC can be depicted as a MIMO system [17]:

Fig. 1 – The fuel-cell powered wheelchair.