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Fuel cell-battery hybrid powered light electric vehicle (golf cart): Influence of fuel cell on the driving performance

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ABSTRACT

A light electric vehicle (golf cart, 5 kW nominal motor power) was integrated with a commercial 1.2 kW PEM fuel cell system, and fuelled by compressed hydrogen (two composite cylinders, 6.8 L/300 bar each). Comparative driving tests in the battery and hybrid (battery + fuel cell) powering modes were performed. The introduction of the fuel cell was shown to result in extending the driving range by 63–110%, when the amount of the stored H_2 fuel varied within 55–100% of the maximum capacity. The operation in the hybrid mode resulted in more stable driving performances, as well as in the increase of the total energy both withdrawn by the vehicle and returned to the vehicle battery during the driving. Statistical analysis of the power patterns taken during the driving in the battery and hybrid-powering modes showed that the latter provided stable operation in a wider power range, including higher frequency and higher average values of the peak power.

1. Introduction

The use of proton exchange membrane fuel cells (PEMFC) in transportation has recently attracted great interest worldwide due to the fact that this type of fuel cell has a number of attractive properties, including positive environmental impact (the only by-products are pure water and heat), high efficiency, low operating temperature, high power density, fast start-up and response to load changes, simplicity, long life, etc. PEMFCs have been successfully demonstrated in various applications such as automobiles, scooters, bicycles, utility vehicles, distributed power generation, backup power, portable power, airplanes, boats and underwater vehicles [1].

There are many publications dealing with fuel cell-battery hybrid powered vehicles and systems. A recent review paper by Pollet et al. [2] highlighted the current status of hybrid, battery and fuel cell electric vehicles from electrochemical and market points of view. The paper analyses the existent engineering solutions, including architectures of hybrid electric drive trains. Cost, durability and energy density are shown to be the main areas where improvements are required to compete with conventional fossil fuels.

Some details relevant to the scope of the present study are outlined below.

Hwang and Chang [3] developed a hybrid powered light electric vehicle (LEV) in which the power system consisted of a

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PEMFC (the major propulsion power) and a lithium-ion battery pack (to provide peak power and to allow regenerative breaking).

Barreras et al. [4] designed and developed a multipurpose utility AWD electric vehicle (two 2.5 kW DC motors) with a hybrid power train based on a PEMFC and batteries. In this design, the vehicle reached a maximum speed of 11 km/h on a flat surface with a maximum power consumption of around 3 kW.

The development of a hybrid PEMFC and its integration into a mini-train is described by Hsiao et al. [5]. The power system is composed of a 200 W PEM fuel cell, four metal hydride (MH) hydrogen storage tanks operating at low pressure, a lead-acid battery pack, and an electronic energy control system. In this configuration, the fuel cell and lead-acid batteries were connected in parallel.

Jiang et al. [6] presented an experimental study on control strategies for active power sharing in a hybrid fuel cell-battery power source. Experimental tests were conducted with three control objectives: maximum power, maximum fuel cell efficiency, and adaptive strategy aimed to maintain a relatively constant battery voltage, by switching between the first two strategies.

Fisher et al. [7] integrated a lithium-ion battery pack, together with its management system, into a hydrogen fuel cell drive train in a lightweight city car. Electronic units were designed to link the drive train components and to allow system start-up, motor control and torque monitoring. The authors concluded that the electronic integration was successful, but the design needed optimisation and fine tuning.

Thounthong et al. [8] proposed an energy system with a 500 W, 50 A PEMFC as a main power source, and battery (68 Ah, 24 V) with supercapacitor (292 F, 30 V, 500 A) as Electrochemical Storage Devices. During starts/stops or other significant variations in load, the storage elements provided the balance of energy during the load transition period, and also absorbed excess energy from regenerative braking.

The development of a fuel cell system and its integration into a lightweight vehicle was presented by Hwang et al. [9]. The fuel cell system consisted of a 3.2 kW PEMFC, a microcontroller and other supporting components including compressed hydrogen cylinder, blower, solenoid valve, pressure regulator, water pump, heat exchanger and sensors. It was found that the vehicle performed satisfactorily over a 100-km drive on a plain route with the average speed about 18 km/h. Measurements also showed that the fuel cell system had an efficiency of over 30% at the power consumption required for vehicle cruise, which is higher than that of a typical Internal Combustion Engine.

The design, fabrication, and testing of an electric bicycle powered by a PEMFC has been reported by Hwang et al. [10]. The system comprises a 300 W PEMFC stack, MH hydrogen storage canisters, air pumps, solenoid valves, cooling fans, pressure and temperature sensors, and a microcontroller. The

Table 1 – Typical operating characteristics of fuel cell powered vehicles. The records selected by *italic* correspond to the solutions where PEM fuel cells are used as on-board range extenders.

Application	Peak power [kW]	Bus voltage [V]	FC stack	Additional energy storage	Hydrogen storage[a]	Reference
Fuel cell powered electric bicycle	0.378	No DC/DC Up to 28	Air cooled PEMFC (0.3 kW)	Battery (start-up only)	MH (6.8 g H_2)	[10]
Mini-train	0.560	No DC/DC 12–24	Air cooled PEMFC (0.2 kW)	Lead-acid battery (18 V)	MH (50 g H_2)	[5]
Hybrid fuel cell wheelchair	0.678	28	Air cooled PEMFC (0.5 kW)	Li-ion battery (24 V, 14.6 Ah)	MH (21 g H_2)	[12]
Hydrogen fuel cell hybrid scooter	*2.5*	*24*	*Air cooled PEMFC (0.5 kW)*	*Lead-acid battery (24 V, 24 Ah)*	*MH (54 g H_2)*	*[13]*
Lightweight fuel cell vehicle	4.0	No DC/DC 38–56	Liquid cooled PEMFC (3.2 kW)	None	CGH2 (125 g H_2)	[9]
All-wheel-drive (AWD) vehicle	5.0	48	Air cooled PEMFC (2 × 1.5 kW)	Lead-acid battery (48 V, 45 Ah)	CGH2 (~0.29 kg H_2)	[4]
Light electric vehicle (LEV)	8.7	48	Liquid cooled PEMFC (6.0 kW)	Li-ion battery (48 V, 40 Ah)	MH (45.8 g H_2)	[3]
Light electric vehicle (golf cart)	*10–12*	*48*	*Air cooled PEMFC (1.2 kW)*	*Lead-acid battery (48 V, 242 Ah)*	*CGH2 (0.28 kg H_2)*	*This work*
Airport electric vehicle	16	80	Air cooled PEMFC (8.5 kW)	Lead-acid battery (84 V, 50 Ah)	CGH2 (1.34 kg H_2)	[14]
Hydrogen-electric hybrid urban vehicle	25	180	High temperature PEMFC (3.2 kW)	Li-ion battery (80 V, 60 Ah)	CGH2 (1.8 kg H_2)	[7]
EnerPac™ 48.1 fuel cell power pack for forklift	40	48	Air cooled PEMFC (8.5 kW)	Ni-MH battery + ultracapacitors (N/A)	CGH2 (0.97 kg H_2)	[15]
Fuel cell hybrid power source for electric forklift	50	80	Liquid cooled PEMFC (2 × 8.0 kW)	Lead-acid battery (80 V, 300 Ah) Ultracapacitors (80 F, 97.2 V)	MH (~0.36 kg H_2)	[16]
Fuel cell hybrid electric city bus	*150*	*557–670*	*Liquid cooled PEMFC (5.0 kW)*	*Na-$NiCl_2$ battery (278 V, 76 Ah)*	*CGH2 (9.6 kg H_2)*	*[17]*

a MH, metal hydride; CGH2, compressed hydrogen gas in cylinders.