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The energy efficiency of an extended range unit involving a polymer exchange membrane fuel cell stack

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Abstract. This article presents the results of experimental investigations on an advanced model of a polymer exchange membrane fuel cell (PEMFC) stack designed to serve as a charging unit for electric vehicle batteries or off-grid distributed power sources. The assembled 720 W PEMFC stack comprises two 360 W modules that can be electrically connected in series or parallel. A liquid cooling system for the PEMFC stack has also been constructed. The dependencies – voltage (U) versus current (I) and current (I) versus electrical power (P) – for single modules, as well as for the electrically connected two-module PEMFC stack, are determined. Additionally, the hydrogen utilization versus the electrical power (P) of the PEMFC stack is examined. The electrical efficiency of the PEMFC stack varies between 42% and 50%, depending on the electrical power. An adjustable DC/DC converter, operating in two modes (step-down or step-up), is proposed as a device to integrate a lithium-ion (Li-ion) battery pack with approximately 720 W PEMFC stack. The electrical architecture of the integrated system, comprising the PEMFC stack, DC/DC converter, and Li-ion battery pack, is investigated and discussed in this paper. It was found that the electrical efficiency of the proposed DC/DC converter varies depending on the electrical power, reaching a peak efficiency of 95%–98%. The environmental benefit, in terms of reducing CO_2 emissions when charging the battery, was also identified.

1 Introduction

In recent years, there has been a marked increase in interest regarding the use of hybrid electrochemical sources, comprising battery packs and fuel cell stacks. These sources are employed in various types of electric transport and in distributed island energy systems with renewable energy sources [1-3]. Battery-electric vehicle (BEV) systems provide a

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dynamic energy supply, high power output, and ecologically friendly alternatives compared to traditional propulsion units that use diesel or petrol combustion engines. One significant challenge for BEVs, particularly in cold weather, is the reduced capacity of batteries and the corresponding decrease in the vehicle range. This behaviour can be attributed primarily to the slowed kinetics of electrochemical processes at lower temperatures. Additionally, significant energy is required to heat the passenger cabin and maintain the battery at an optimal operating temperature. If the battery becomes too cold, it can degrade significantly and have a considerably shortened lifespan [4-6]. Batteries also face limitations in terms of charging time and range. Conversely, hydrogen-oxygen fuel cells powering electrical engines offer ranges and charging times comparable to those of combustion engine-powered vehicles. Hydrogen, whether for transport or stationary applications, must first be produced from primary sources (mainly natural gas) or via the water electrolysis process, then compressed and stored in composite cylinders at high pressures of 350–700 bar. The production of high-purity hydrogen and its compression require substantial energy and involve significant investment and operational costs. In some instances, there has been a shift towards developing lower electrical power fuel cell stacks compared to their traditional use in powertrains. These additional power sources can charge the battery, thereby extending its operational time. Employing a fuel cell power source that recharges the battery both during operation and while stationary renders various types of electric vehicles less dependent on a network of electric chargers or the challenges associated with locating them.

The development of energy-efficient fuel cell extenders with suitable electrical architecture poses a significant challenge for applications in electric transport and off-grid distributed power systems [7, 8]. Although commercial solutions for complete battery extenders with fuel cells for mobile and stationary applications are available, there is still a need to enhance their reliability and energy efficiency and to develop new flexible solutions tailored to new vehicles and energy systems. The utility of fuel cells as range extender devices differs from their application as primary sources in powertrain systems, presenting several design and operational challenges. A crucial component in the fuel cell sector is the DC/DC converter, which equalises the voltage level between the battery and the fuel cell stack in hybrid power sources. It plays a vital role in managing the distribution and quality of electrical energy, adjusting to the variable electrical load in real time for electric motors or other electrical loads [9, 10].

The aim of this paper is to present the results from the development and investigation of two modular polymer exchange membrane fuel cell (PEMFC) stacks, and DC/DC converters utilised as components of fuel cells for range extension. Special attention is devoted to examining the energy efficiency of an integrated electrical system designed for charging lithium-ion (Li-ion) battery packs, with varied operations of the DC/DC converter in both step-up and step-down modes.

2 Experiment

The experimental setup was designed to study the charging process of an electrochemical battery using the energy generated by a hydrogen-oxygen fuel cell stack. The following components were selected:

a) Li-ion battery module: Consisting of single cells 18650 with an electrical configuration of 16S10P, this module comprises 160 Li-ion cells connected in a 16s10p configuration and has a nominal capacity of approximately 26 Ah.

b) This stack, a 720 W low-temperature polymer exchange membrane fuel cell (LT-PEMFC), is cooled with a liquid medium and constructed from two PEMFC modules.

c) Adjustable DC/DC converter: This device operates in either step-down or step-up modes and is equipped with potentiometers enabling a wide range of settings, including (1) limiting the maximum current drawn from the LT PEMFC stack, (2) setting the minimum voltage threshold for the LT-PEMFC stack, (3) adjusting the output voltage (set point) of the converter, and (4) limiting the maximum output current to the battery. The wide range of adjustable parameters allows for the reduction (step-down mode) or increase (step-up mode) of the voltage from the fuel cell stack, thereby protecting the LT-PEMFC stack and the electrochemical battery from operating under unfavourable or hazardous conditions.

In Tables 1 to Table 3, the main features of the used devices – the electrochemical Li-ion battery, PEMFC stack, and DC/DC converter – are detailed for the experimental studies.

Table 1. Electrical parameters of the Li-ion battery pack (Libra battery, producer BTO Lodz, Poland).

Parameter	Unit	Value
Rated voltage	V	60
Charging voltage (max.)	V	67
Discharging voltage (min.)	V	40
Discharging current (max.)	A	40
Charging current (max.)	A	5
Capacity	Ah	26
Energy	Wh	1560

Table 2. Electrical parameters of the PEMFC stack connected in series and parallel connections.

Parameter [Unit]	A or B module FC42/360	A and B modules (Electrical connections)	
		In series	In parallel
P [W]	360	720	720
OCV[V]	37.5	75	37.5
I max [A]	30	30	60
U, I for P_{max}	24 V 15 A	48 V 15 A	24 V 30 A

Table 3. Electrical parameters of the elaborated DC/DC adjustable converter.

Parameter	Unit	Value
In voltage	V	15–160
In current max	A	40 (adjustable)
Out voltage (adjustable)	V	15–80
Out current (Iout)	A	40
Maximum power (24V)	W	3,000

Figure 1 illustrates the experimental setup for the elaborated two-module PEMFC stack during battery charging using the elaborated additional DC/DC converter.

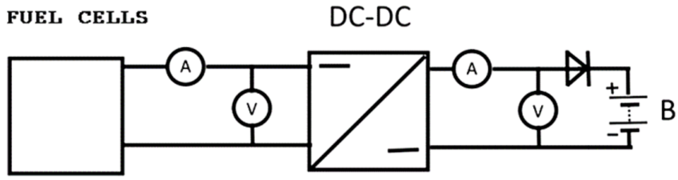

Fig. 1. The experimental setup for an elaborated two-module PEMFC stack during battery charging using the elaborated additional DC/DC converter.

3 Results

In Figure 2a, the variation in voltage (*U*), current (*I*), and charge (*Q*) over time (*t*) during discharge (constant current I = 5 A) of a Li-ion battery pack is depicted.

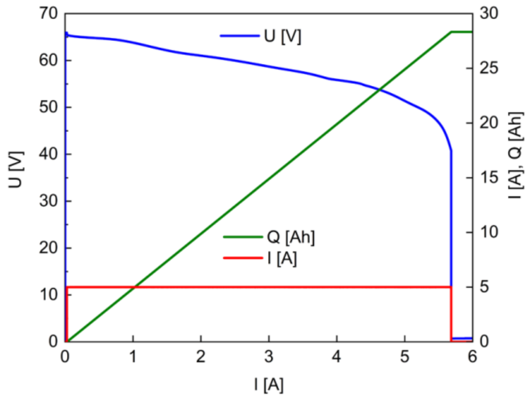

Fig. 2a. Curve showing voltage (*U*), current (*I*), and charge (*Q*) versus time (*t*) recorded while discharging the Li-ion battery.

The battery voltage gradually decreases from a maximum of 67 V DC (fully charged) to 40 V DC (fully discharged). At this voltage level, approximately 40 V, the battery management system deactivates the electrical load of the battery to protect it from a dangerously deep discharge.

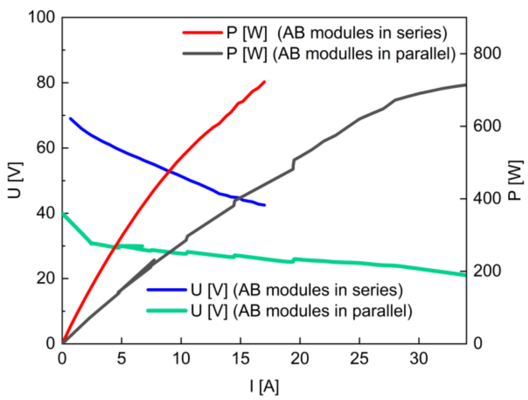

Fig. 2b. Dependencies of voltage (*U*), current (*I*), or electrical power (*P*) observed for series connections of A and B modules as well as their parallel connections.

Detailed electrical analyses of the 720 W LT-PEMFC stack were carried out. The electrical parameters of this stack, illustrated in Figure 2b, correspond to an LT-PEMFC stack operating with series and parallel connections of the A and B modules. From the dependencies shown in Figure 2b, it is evident that the PEMFC stack operates at nominal power, approximately 720 W, in both configurations examined. During the operation of the two-module PEMFC stack, the temperature of the cooling medium was maintained at 50°C. Figure 3 illustrates the relationship between hydrogen flux and electrical power (P).

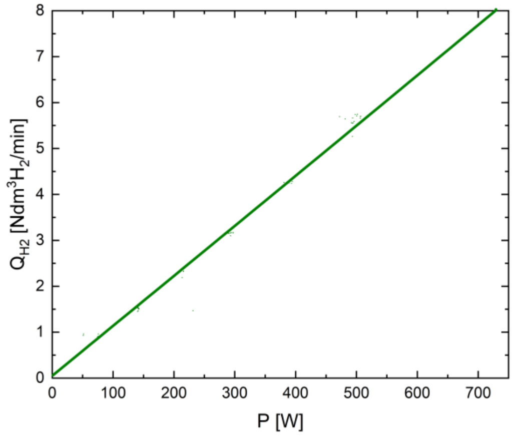

Fig. 3. Dependence of hydrogen flux (Q_{H2}) versus electrical power (P) for the 720 W two-module PEMFC stack.

The efficiency estimated from hydrogen flux measurements and hydrogen utilisation in the two-module PEMFC stacks ranges from 42% to 52%. The observed values of hydrogen utilisation versus electrical power (P) and electrical efficiency are in good agreement with existing literature data for PEMFC stacks [11-12]. The determined electrical parameters of the PEMFC stack make it suitable for charging batteries.

In Figure 4a, the electrical waveforms recorded for the DC/DC converter output voltage ($U_{battery}$) and electrical power output (P_{out}) during the charging of the Li-ion battery pack are presented.

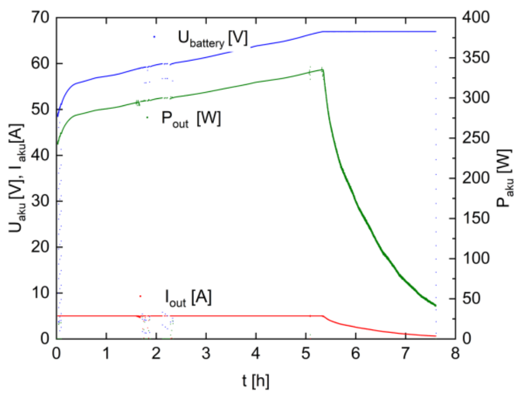

Fig. 4a. Curves of voltage ($U_{battery}$) of the Li-ion battery pack; current (I_{out}) and electrical power (P_{out}) at the output of the DC/DC converter versus time. The DC/DC converter operates in step-down mode.

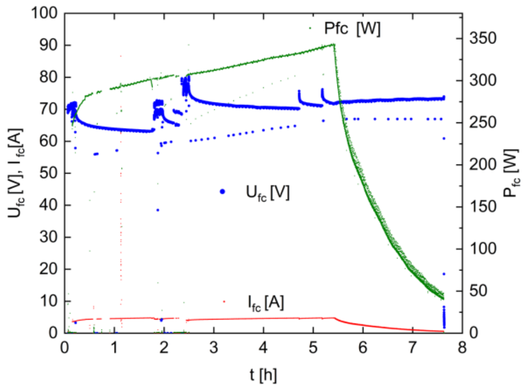

Fig. 4b. Dependencies of the variations in the electrical parameters – fuel cell voltage (U_{fc}), load current (I_{fc}), and power (P_{fc}) of two series-connected modules of the LT-PEMFC fuel cell stack – versus time.

Figure 4b shows the electrical waveforms of voltage ($U_{battery}$) of the Li-ion battery pack, current (I_{out}), and electrical power (P_{out}) versus time (t) at the output of the DC/DC converter, which operates in step-down mode. These dependencies were recorded while charging the Li-ion battery in constant current mode (I_{out} • 5 A) until reaching the maximum permissible voltage of $U_{battery}$ = 67 V. The electrical performance of the PEMFC stack is also analysed. Figure 4b displays the variations in the voltage (U), current (I_{fc}), and power (P) of the series-connected modules of the PEMFC fuel cell stack over time. Throughout the charging process, the PEMFC stack voltage (U_{fc}) is continuously reduced by the DC/DC converter to match the battery voltage. The voltage of the Li-ion battery pack rises from 40 V (discharged) to 67 V (fully charged).

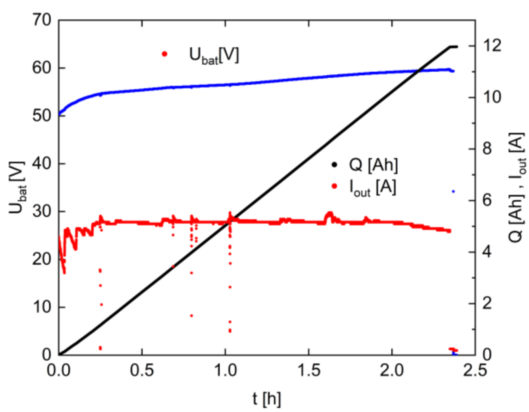

Fig. 5a. Variation of voltage (U_{bat}), current (I_{out}), and charge (Q [Ah]) for the Li-ion battery during charging by the DC/DC converter (step-up boost).

Figure 5a shows the changes in voltage (Ubat), current (Iout), and charge (Q [Ah]) for the Li-ion battery pack while charging by the DC/DC converter (step-up boost). The electrical charge, Q = 12 [Ah], was delivered to the Li-ion battery over a 2.5-hour charging period. This corresponds to about half the nominal capacity of the battery.

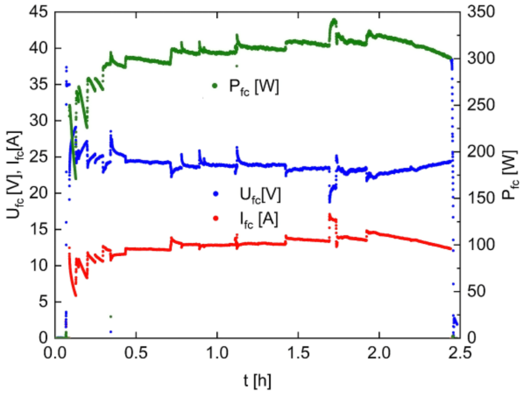

Fig. 5b. Waveforms of voltage (U_{fc}), current (I_{fc}), and power (P_{fc}) of the LT-PEMFC stack over time (*t*) while supplying the input of the DC/DC converter operating in voltage boost mode.

Figure 5b presents the waveforms of the current (Ifc) and voltage (Ufc) of the LT-PEMFC stack over time (t). Under these conditions, the electrical power derived from the PEMFC stack is approximately 300–320 W. The electrical parameters of the PEMFC stack, such as the current (Ifc), range from 10–15 A, corresponding to a voltage range of 22–26 V DC. The average power drawn from the fuel cell stack by the DC/DC converter while charging the battery is 310 W. According to Figure 2, the two-module PEMFC stack operating with an electrical power of approximately 310 W consumes 3.1 Ndm3 H2/min. Over 5.5 hours while charging the Li-ion battery, it will consume a total hydrogen volume of 17 Ndm3 H2.

If we utilise so-called green hydrogen produced from renewable sources, we will not emit CO2 to charge the batteries. In contrast, if we powered the converter with energy from the power grid, it would consume 1.7 kWh. In the case of the Polish power grid, where emissions are factored at 685 kg/MWh for end-users of electricity, consuming 1.7 kWh to charge the battery would result in emissions of approximately 1.12 kg CO2.

4 Conclusion

This paper has presented the laboratory model of a PEMFC fuel cell stack designed to extend the operational range alongside a specialised PEMFC fuel cell stack and an adjustable DC/DC converter. The electrical investigations confirm that the designed modular PEMFC stack can deliver the necessary electrical power of approximately 720 W, whether in series or parallel configurations. The electrical efficiency of this modular PEMFC stack ranges between 40%–52%. Furthermore, the utility of an adjustable DC/DC converter, serving as an integrative device between the PEMFC stack and the Li-ion battery, has been demonstrated and examined. The DC/DC converter's electrical efficiency, operating in both step-up and step-down modes, fluctuates with the electrical power, achieving a peak efficiency of 95%–98% within the 300–350 W power range.

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