Chapter 13
Energy Efficiency of PEM Fuel Cell Hybrid Power Source

Nicu Bizon and Mircea Raceanu

Abstract The chapter deals with a single DC bus hybrid configuration of a power source required for an automotive application. Such system architecture is the best choice for interconnecting multiple energy sources in order to meet the load profile in the most efficient way. This work analyzes a new PEM Fuel Cell stack-Hybrid Power Source (PEMFCs-HPS) topology consisting of a 5 kW PEMFC stack (primary source of power) and a bank of ultracapacitors (130 F, 56 V, 57 Wh) (auxiliary power source) to fulfill the high energy and high power requirements of the vehicle applications, wherein the power demand is impulsive rather than constant. This topology uses three programmable unidirectional DC/DC converters which connects the PEMFCs, the UC and the programmable electronic load. The energy management strategy (EMS) for different power sources has great effect in decreasing the fuel consumption, increasing the performance and the lifetime of the fuel cells. The proposed EMS is based on the FC efficiency map and on the state of charge of the UC. The EMS is used to split the power between the PEMFCs and the UC in the hybrid arrangement to fulfil the power requirement, which depends on the operating conditions considering the optimum power of PEMFCs and UC. An algorithm the EMS is able to achieve the steady-state PEMFCs operating with minimum hydrogen consumption and the UC state of charge (SoC) maintaining at values higher than 20%. The system ability to efficiently follow the load variations under that EMS is also presented. The consumption of hydrogen was reduced by

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N. Bizon et al. (eds.), *Energy Harvesting and Energy Efficiency*, Lecture Notes in Energy 37, DOI 10.1007/978-3-319-49875-1_13

11.8% in comparison with the system without UC. The experimental data acquisition system is monitored and controlled using the NI Labview® software with the NI Compact-RIO hardware.

Keywords Hybrid power source · PEM fuel cell · Ultracapacitor · Energy management

Abbreviation and Acronyms

PEMFCs	Proton Exchange Membrane Fuel Cell stack
UC	Ultracapacitor
SoC	State of Charge
EMS	Energy Management Strategy
HPS	Hybrid Power Sources
BoP	Balance of Plant
DC	Direct Current

13.1 Introduction

Due to their operating principle through which hydrogen and oxygen are electrochemically converted into electricity, with high conversion efficiency, low temperature operation and practically no pollutant emissions, Proton Exchange Membrane Fuel Cell stack (PEMFCs) became very attractive for both mobile and stationary power applications [1–3].

Unfortunately, PEMFCs are characterized by relatively poor dynamics, being unable to follow fast transients in power demand. Besides that, it was observed that operating a fuel cell on pulsed load causes its relatively fast degradation [4, 5]. One of the main weak points of the PEMFCs is its slow dynamics mainly due to the hydrogen and air supply subsystems [6, 7]. The fuel starvation phenomenon will occur during fast load demand, which will cause a high voltage drop in a short time [8]. To solve this problem, the PEMFCs must to be efficiently operated in conjunction with other energy sources or energy storage systems [9, 10].

Taking into account these aspects we can conclude that adding on an energy storage system (ESS) to the PEMFCs power source is a necessary step [11, 12]. These are some reasons of adding an energy storage system (ESS) to the PEMFCs power system. The PEMFCs/ESS hybrid could be operated so that PEMFCs should meet the load power demand at steady-state and ESS (Energy Storage System) is buffering power transients [13].

Rechargeable batteries are the most common devices used for electric energy storage, but recent advances in manufacturing and materials technology made that ultracapacitors (UC) into be considered strong competitors. Unlike battery storage, based on chemical reactions, which gives a slower energy transfer process in both directions, UCs store energy electrostatically and have very low internal resistance, resulting in very fast charge/discharge rates with very little power loss and great overall efficiencies [3, 14]. It seems that the energy density remains the last advantage that batteries have over ultracapacitors, but only transitory, new better materials resulting in narrowing the gap between them.

Hybrid Power Sources (HPS) in general and PEMFCs/UC sources in particular are currently being intensively investigated because of their use in stationary and vehicular applications [4, 15, 16]. PEMFCs are designed for continuous energy supply and are best operated at constant operating conditions [17]. They work poorly in the presence of power fluctuations and cannot handle high power demands. UCs, on the other hand, have relatively very low energy densities and very high power densities. UCs are used for energy storage and to protect the FC from power transients. The purpose of any hybrid power sources that involves more than one device is to put together the advantage of the various devices in one single system and increase the fuel cell operating life and improve the device efficiency [18].

In specialized literature, passive and active hybrid configurations are usually presented separately. The passive hybrid configuration is based on parallel connection between main and auxiliary sources. In a passive configuration the choice of energy management algorithms are greatly limited [19]. Active hybrid configuration needs the introduction of energy conversion steps between main and auxiliary sources. This provides great flexibility during design and different configurations can be realized. Through the power converters, power-sharing between the main and auxiliary source can be successfully implemented.

Various control strategies to manage energy in a hybrid system [20–22] have been proposed in various applications. In some papers [23, 24], EMS are applied to high-power electric vehicles based on FC, battery and UC. Other papers [25–28] use control strategies based on fuzzy logic control, which determine the operating point of the power converter FC depending on the load power and the battery state of charge (SoC).

In the paper [29] three energy management strategies for fuel cell hybrid vehicles were presented. The strategies are based on the knowledge of the fuel cell efficiency map: two of them are heuristic type strategies and the third strategy is based on constrained nonlinear programming.

Due to the different characteristics of the various sources of energy, efficiency and fuel economy the HPS mainly depend on an adequate strategy for the energy management. In this chapter, the Energy Management Strategy between PEMFCs and UC is based on setting a number of power sub-regions of 1000 W in the range of 1–5 kW, in which we know the point of maximum efficiency, respectively the gas consumption in those sub-regions. Each sub-region has a maximum efficiency point while PEMFCs works in stationary conditions, at the lowest consumption of the hydrogen. Depending on the load and on the UC state of charge (SoC > 20%) the power that is generated by the PEMFCs is established, according to the fuel cell power and efficiency map the hydrogen and air supply flows are established. The EMS algorithm identifies the sub-region in which the PEMFCs works with the maximum efficiency. If the power supplied by the fuel cell is greater than the power loads, the EMS will manage the UC surplus power through the DC/DC charge UC and this charging is controlled. The EMS algorithm is developed in NI LabVIEW using a state machine architecture, implemented in FPGA to run at a speed of execution of 100 μs. The novelty of this article is to use a DC/DC converter which is connected between PEMFCs and UC, and is designed to load the power excess in UC, thus making the PEMFCs to operate in regime static. The decreasing of hydrogen consumption depends on the operation of PEMFCs in the maximum efficiency point in that sub-region. The EMS algorithm proposed is tested experimentally and the results show favourable performances.

The chapter is organized as follows: Sect. 13.2 introduces the configuration of the HPS and describes the experimental setup including the NI Compact-RIO hardware; Sect. 13.3 proposes the EMS based on the fuel cell efficiency map and on the state of charge of the UC including the NI Labview software; In Sect. 13.4, the experimental results are presented and discussed; and finally the conclusions are summarized in Sect. 13.5.

13.2 Hybrid Power Sources Design

13.2.1 General Architecture of the Hybrid Power Source

In order to increase the power of the fuel cells from 10 to 90% is about 2 s are required [30]. On the other hand, the sudden variations of the load power could lead to a dramatic decrease of the life of cell. Hybridized fuel cell power sources for automotive applications can tolerate in this way much more transitory than a single cell. The hybrid system has a much better dynamic response, thus contributing to increasing the lifetime of the fuel cells.

Figure 13.1 shows a generic HPS with two power flows (FC and UC), the required power load of the fuel cell being provided by a unidirectional converter.

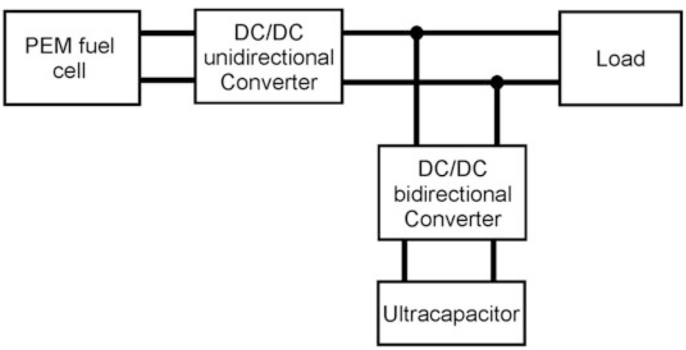

Fig. 13.1 Generic architecture of the FC/UC power source

UC is directly connected to the load through a bidirectional converter. It provides a good suppression of transition and peak power. The energy stored in the UC is not limited to the fuel cell or the load. The power of each source can be controlled. UC shows its usefulness when braking regenerative.

The disadvantage of this architecture is that the fuel cell connection always aims the load profile. The power management strategy is more difficult for small variations in the load. To remove these disadvantages, between fuel cell and UC, an unidirectional converter DC/DC was inserted. The role of this converter is to guide the surplus power from the fuel cell to the UC.

13.2.2 Proposed Architecture of the Hybrid Power Source

A hybrid fuel cell/ultracapacitor architecture (photos in Fig. 13.2) is proposed for a FC power system intended to be used in an automotive application. A single DC BUS topology was chosen because it seems to be the best choice for interconnecting multiple energy sources in order to meet the load profile in the most efficient way [31].

The power system, schematically presented in Fig. 13.3, is based on a 40 cells, 5 kW, 40 V NEDSTACK PEM Fuel cell stack and a 23 cells, 130 F, 56 V MAXWELL Ultracapacitor bank.

The PEMFC stack is fed with humidified hydrogen and air, at a stoichiometry of 1.25 and 2, respectively. The load of the system is represented by a 60 V, 240 A, 5 kW IT8518C electronic load.

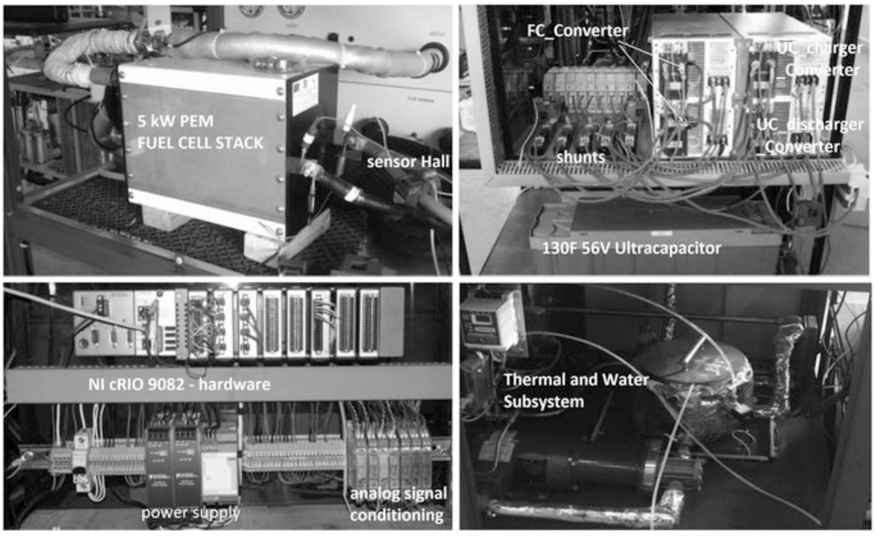

Fig. 13.2 Test bench PEMFCs/UC—Hybrid Power Sources for real-time control

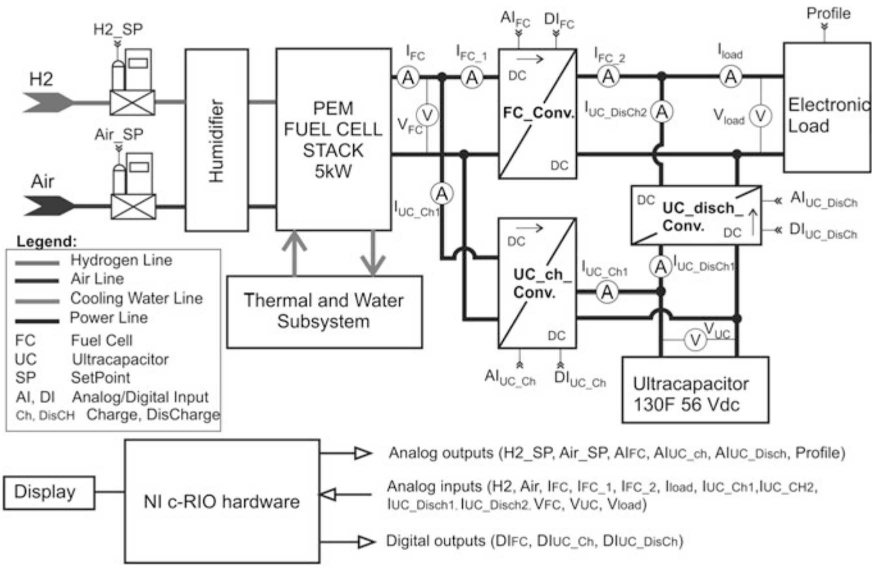

Fig. 13.3 Proposed block diagram of the FCS/UC power source

Since the power system has two sources, it takes at least two converters to control the bus voltage and the power split between the two sources. The independent control through the DC/DC converters of both FC and UC allows combining the energy sources on a BUS, each operating at a different voltage. As it is shown in Fig. 13.2, a unidirectional DC/DC boost converter is used to connect the fuel cell stack to the bus (DC/DC boost FC_Conv), and two unidirectional DC/DC boost converters are used to connect the ultracapacitor bank to the FCs for charging (DC/DC boost UC_ch_Conv) and to the DC BUS for discharging (DC/DC boost UC_disch_Conv), respectively. The latter ones could be replaced by a single bi-directional converter.

The power system objective is to meet the load power demand at the lowest fuel consumption and to reduce the transitional demands for the PEMFCs, simultaneously with keeping the UC State of Charge (SoC) above 20%. SoC is defined as the UC voltage multiplied by 100 over its maximum rated voltage and ranges from 0% at no charge to 100% at full charge.

13.2.3 PEM Fuel Cell Stack

The main part of the Hybrid Power Sources is the fuel cell stack, where the electrochemical reaction between the fuel (hydrogen) and the oxidant (usually oxygen from air) occurs, producing electricity and heat. The behaviour of the PEM fuel cell stack depends of particularly variables. A Nedstack P5.0-40 PEMFCs,

Table 13.1 Product specifications and operating conditions

Specification	Value
Active area	250 cm^2
Stack output rated parameters	5000 W @ 36 VDC
Stack maximum voltage	40 VDC
Cell voltage	0.95–0.5 V per cell
Minimum allowable cell voltage	0.3 V for the lowest performing cell
Current range	0–230 A
Maximum allowable current	230 A
Nominal operating temperature	65 °C
MEA pressure difference	<0.3 bar

composed from 40 cells for a nominal maximum power of 5 kW, operated at atmospheric pressure to about 3 bar, was used for experimental investigation [32]. The operating voltage of the stack is a function of current and decreased with increasing power (Table 13.1).

The test bench is represented by a hydrogen supply subsystem to the anode, air supply subsystem to the cathode, de-ionized water serving as coolant in the cooling channel, de-ionized water to humidify the hydrogen and the air flow, a programmable electronic load, DC/DC converters, a control process and an interface.

High purity hydrogen (99.995%) and compressed air are used as a fuel and as an oxidant. The hydrogen is supplied as fuel and air is supplied as oxidant reactant. Both reactants are controlled at the entrance of the fuel cell stack with two mass flow controllers, located before the bubble humidifiers. Pressures of the anode and cathode sides are controlled by back pressure regulators (Alicat Instruments). The voltage set point for the flow rates and pressures are connected to the NI 9263 analog output module. Humidity levels are verified time to time with downstream humidity sensors. The maximum mass flow rates are calculated at the maximum power demand, maximum stoichiometric ratios, and the minimum cell voltage, taking into account the specification of the 5000 W PEM fuel cell. The minimum cell voltage is 0.5 V because any voltage below this value may result in deterioration of the PEM fuel cell stack.

An important parameter namely the temperature is measured by T-type thermocouples inserted in a NI 9213 thermocouple input module system and regulated by a cooling water circuit which includes a water pump, a needle valve for flow water control, a cold exchanger and a heater. Another water circuit is used to condense the water in the gaseous phase.

The tests were carried out by initialling the PEMFCs in flow-through anode fuelling mode. This operation was necessary to estimate the current/voltage reference characteristics. The next step was focused on the comparison between the PEMFCs as single equipment and the PEMFCs & BoP Balance of Plant (BoP) assembly.

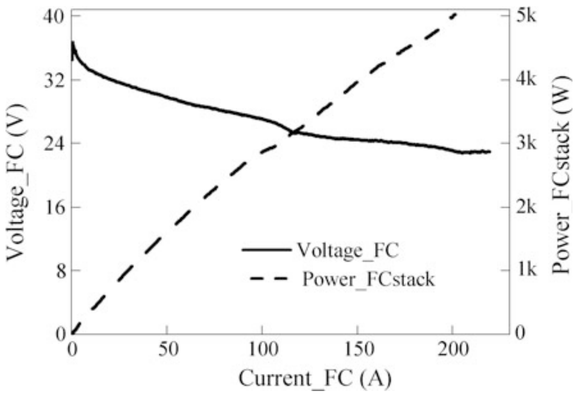

Fig. 13.4 Polarization curve for 5 kW PEM Fuel Cell power stack [33]

The reference characteristics of the NEDSTACK FCS were determined by supplying pure hydrogen at anode and air at cathode, in the following conditions:

- Anode supply stoichiometry of 1.25 and cathode stoichiometry of 2.0;
- Relative humidity: 80–100% for gaseous phase;
- Stack temperature: 65 °C.

The obtained polarization curve (Fig. 13.4), illustrates the power versus current characteristic. We have to mention that the hydrogen and air flow rates are proportional to the current produced by the stack. Moreover, the consumptions of reactants according to the power fuel cells, is presented in Fig. 13.5.

The polarization curve obtained herein provides the ideal electrochemical results from the fuel cell stack. It could be considered as reference point for adjusting of the stoichiometric ratios, during sudden load. During this test the PEM fuel cell stack voltage decreases proportionally with the current and reaches the minimum corresponding to the maximum current. The PEM fuel cell stack power increases proportionally with the current and the maximum is obtained at the maximum current (230 A) [6, 33].

13.2.4 Ultracapacitor

Ultracapacitors are devices for storing energy much more attractive than batteries, which have a much higher yield, higher power density and the number of charge/discharge up to a million times. The energy density of UC-s is much higher than traditional electrolytic capacitors, therefore, they can act as a bridge between the high power capacitors and high energy batteries.

The ultracapacitor used in this application is produced by Maxwell. The ultracapacitor electrolyte uses as an organic substance that is called acetonitrile. This

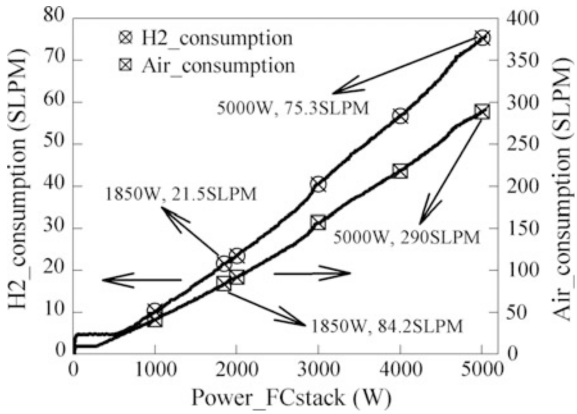

Fig. 13.5 The hydrogen and air consumption depending on the PEMFCs power

Table 13.2 Specification of the ultracapacitor

Manufacturer	Maxwell
Type	BMODO130-P056
Rated voltage	56 V
Rated capacitance C_{UC}	130 F
Maxim ESR DC initial	8.1 mΩ la 100 A
Specific energy	3.1 Wh/kg
Specific power	2,600 W/kg
Number of cells	23
Stored energy	57 Wh
Mass	18 kg

allows a higher operating voltage than an aqueous electrolyte. Organic electrolyte has a lower freezing point allowing use in a wider range of temperatures (−40 to +40 °C). Carbon electrodes are activated and use as a cellulose separator. Its specifications are shown in Table 13.2. The reason for the high nominal voltage VUC, max = 56 V means that several cells are connected in series in order to form a module or a bank of ultracapcitoars. Next it will be labelled "UC—ultracapacitor".

The ultracapacitor must not be exploited over the specified maximum voltage. If it accidentally exceeds the upper limit of the mentioned voltage, it will result in shortened life and, in extreme cases, flue gas accumulated in the cell, due to overvoltage condition. To ensure maximum performance and longer life, the operating voltage should be between nominal voltage (56 V) and half the voltage (28 V). Usually in this operating range, the energy available is about 75%. Figure 13.6 shows the ultracapacitor characteristics of discharge at different current constant values.

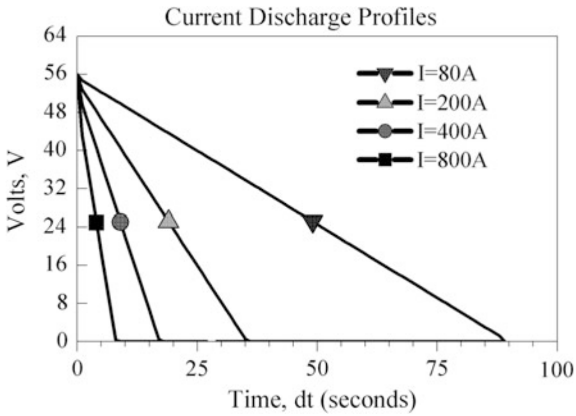

Fig. 13.6 Current discharge profiles for different values

13.2.5 DC/DC Boost Converters

Our application is built with three DC/DC unidirectional converters: the first converter is disposed between the PEMFCs and load, it has an output power of 5000 W (DC/DC boost FC_Conv.); the second converter is placed between PEMFCs and UC, it has a power of 1,250 W, and it is designed to load the excess power from the PEMFCs in the UC (DC/DC boost UC_ch. Conv.); the third converter is connected between UC and load, and it is designed to supplement the power flow, when the PEMFCs power is smaller than the load power, the power output being 1,250 W (DC/DC boost UC_Disch. Conv.). The DCC5500 type converters are built by the company Ripenergy.

The characteristics of the converter are: variable input voltage: 20–40 V; output voltage: 40–60 V; adjustable output voltage via 0–10 V input signal; remote shut down with digital output from PLC (Programmable Logic Controller) and efficiency: 75–94% depending on input/output combination.

13.2.6 NI Compact-RIO Hardware

The test station is fully automated using a supervisory control and data acquisition system that utilizes the NI CompactRIO 9082 platform. The system consists of an embedded controller for communication and processing, a reconfigurable chassis housing the user-programmable FPGA and graphical LabVIEW software for rapid real-time, windows and FPGA programming.

The system has two NI 9205 analog input modules to read the analog parameters of the fuel cell stack, one NI 9263 analog output module for control mass-flow/pressure controllers and DC/DC converters, one NI 9213 thermocouple input module, one NI 9481 relay module for solenoid valve control and one NI 9401 digital I/O module to output the PWM (pulse-with modulation) for the heating SSR (solid state relay) and coupling/decoupling of the DC/DC converters.

The aim of the hardware system was to control the power between the PEMFCs and the UC, which depends on the operating conditions by taking into account the optimum power of the PEMFCs and the UC state of charge, by adjusting of their control loops of the DC/DC converters. The reconfigurable input and output functionality of the cRIO-9082 allowing a rapid implementation of real time (RT) and field programmable gate array (FPGA) capabilities, with a closed loop proportional integral derivative (PID) control scheme for the hydrogen and air/oxygen mass flows using a high-level LabView programming interface.

13.3 Energy Management Strategy

13.3.1 Efficiency Analysis for the Hybrid PEMFCs/UC Power Source

The load power at all times, $P_{load}(t)$, has to be supplied by the FC power, $P_{FC}(t)$, and by the UC power, $P_{UC}(t)$, so that the power balance on the DC bus must be fulfilled permanently.

At every moment,

$$P_{FC}(t) \cdot \eta_{FC} \cdot \eta_{FC/B} + P_{UC}(t) \cdot \eta_{UC} \cdot \eta_{FC/UC} \cdot \eta_{UC/B} = P_{load}(t), \forall t \tag{13.1}$$

where: $\eta_{FC}, \eta_{FC/B}, \eta_{UC}, \eta_{FC/UC}, \eta_{UC/B}$ are respectively the efficiency of the FC, the efficiency of the power converter connecting the FC to the BUS, the efficiency of the UC, the efficiency of the UC charging power converter and the efficiency of the power converter connecting the UC to the BUS.

In order to set up an Energy Management Strategy (EMS) for the hybrid PEMFCs/UC power source that meets the above mentioned objective, the 5 kW PEMFCs efficiency versus load power characteristic was determined.

As presented in the Fig. 13.7, there is an operational zone where the PEMFCs efficiency is the highest, and another zone, where the PEMFCs efficiency is unacceptably low. This efficiency map shape at low power is due to the need of using almost all the generated power to compensate the parasitic power losses.

The implemented EMS is intended to solve the problem of the power split between the PEMFCs and the UC, in compliance to Eq. (13.1) and in accordance with the following constraints:

- restricted PEMFCs power dynamics to avoid damage the stack;
- using UC state of charge as a parameter to be maintained in the fixed limits: 20–100%.

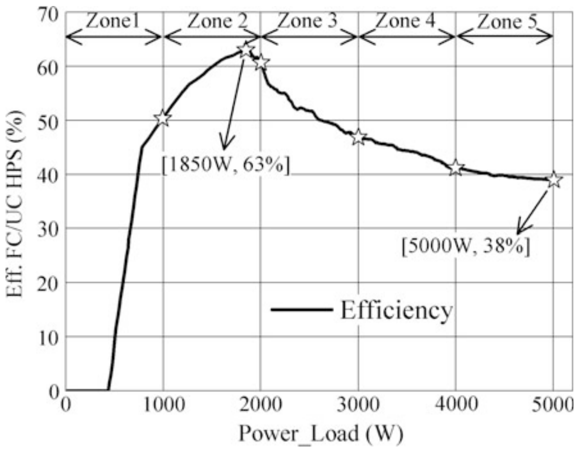

Fig. 13.7 Fuel cell efficiency versus load demand

In addition to these constraints, the hydrogen consumption has to be monitored.

As we already mentioned, a PEMFCs could not operate alone and some sub-systems to provide and control the operating conditions and parameters are necessary, but not limited to, pumps, blowers, heat-exchangers, sensors and controllers, all being named BoP. The power conditioning system, including the DC/DC converter, is consuming power too [33].

The PEMFCs efficiency is defined as the ratio between the maximum generated power and the heating power of the hydrogen consumed at anode to generate that power [34].

$$\varepsilon_{st} = \frac{P_{st}}{P_{H_2}} = I_{st} \cdot \frac{V_{st}}{M_{H_2}} \cdot m_{H_2} \cdot \Delta h \quad (13.2)$$

where subscript *st* refers to the stack and H_2 refers to hydrogen, ε means efficiency, *P*—power, *I*—current, *V*—voltage, *m*—mass flow, *M*—molar mass, and *Δh*—enthalpy.

The consumed hydrogen mass flow is measured, and the generated power results from the measured generated voltage multiplied by the measured generated current.

The fuel cells based energy system efficiency is defined as the ratio between the load power and the heating power of the hydrogen consumed at anode to generate that power.

$$\varepsilon_{system} = \frac{P_{load}}{P_{H_2}} = I_{load} * \frac{V_{load}}{M_{H_2}} * m_{H_2} * \Delta h \quad (13.3)$$

where subscript *system* refers to the PEMFCs & BoP assembly and *load* refers to the energy user.

As concerning the (PEMFCs & BoP) system the efficiency is zero for the stack generated power lower than 0.45 kW, because all the generated power is used for

BoP supply, and it begins to rise, reaching up to 63% for a generated power of 1850 W. Over that limit, a slight decrease in system efficiency is noticed, because of the greater increase in BoP supply when the generated power is increasing.

13.3.2 EMS Algorithm

The EMS algorithm is based on the above mentioned PEMFCs efficiency map and was implemented in one main routine and five subroutines.

In Fig. 13.8 the main routine schematic is presented. This routine is programmed into a technical "state machine" and it is called the software interface (Fig. 13.10). The first block decision of the routine, *Run Control*, if it is true (controlled from the software interface) then the EMS algorithm is ran. The last block of decision, *Stop Control*, if it is true then the controller switches the safety system (gas flow stops and lock converters). As a method to reduce the PEMFCs transients, its power range was divided in 5 equal sub-domains (1000 W), depending on the load power, P_L, the algorithm execute one of the sequences from 1 to 5. The PEMFCs power on each of them was being set to the value corresponding to the local maximum efficiency and allowing in this way a smooth transition. In order to avoid operating

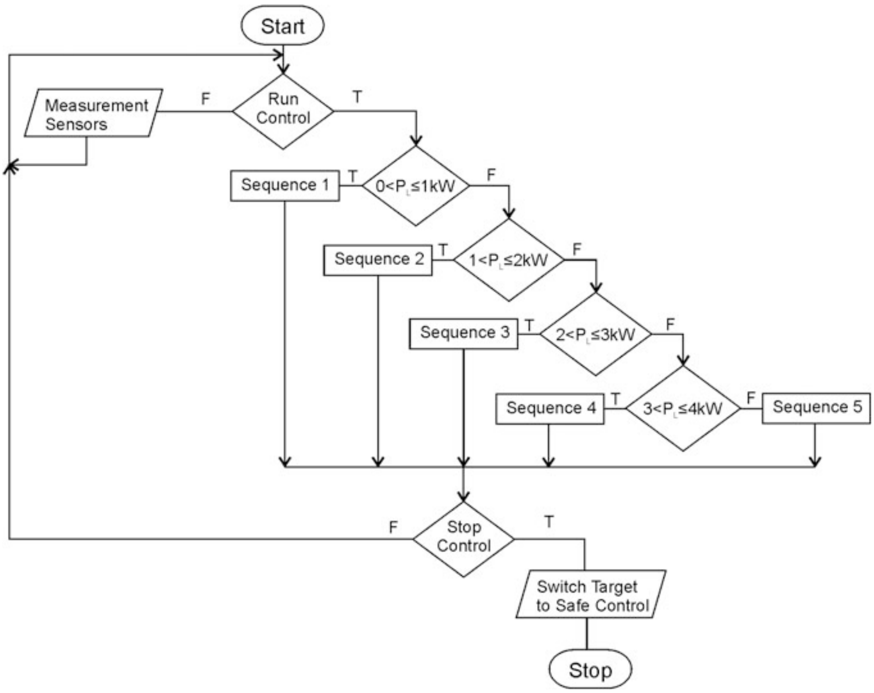

Fig. 13.8 EMS main routine

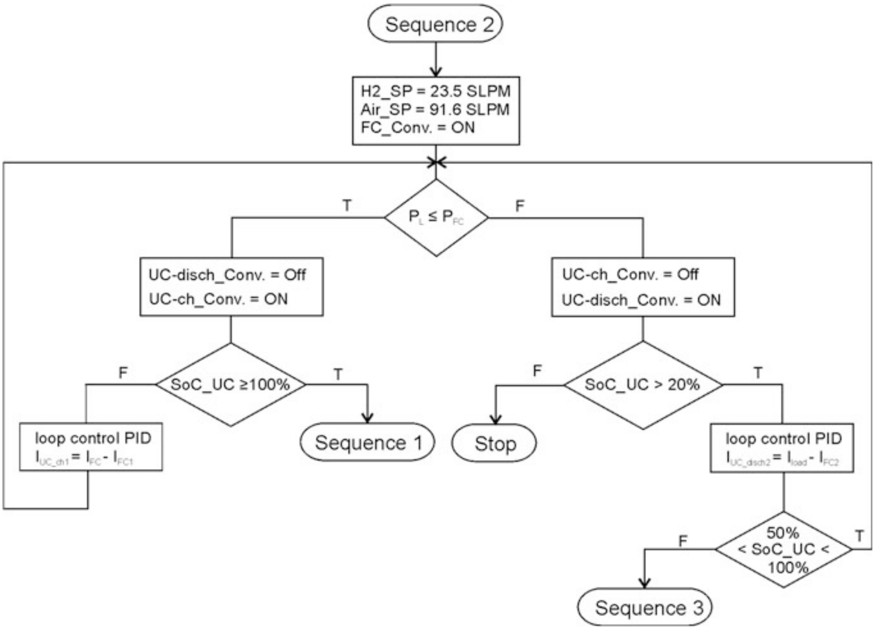

Fig. 13.9 Schematic of the sub-routine 2

the PEMFCs in the low efficiency zone, at the power system switch-on the PEMFCs operational point will be always set to the highest efficiency point by feeding it with the corresponding hydrogen and air flows.

In the Fig. 13.9 one of the sequences is presented (Sequence 2) was chosen as an example, but it should be noted that all sequences are logically identical. The input signals of the EMS algorithm are SoC of the ultracapacitor (*SoC_UC*), fuel cell power (P_{FC}), load power (P_L), fuel cell total current (I_{FC}), load current (I_L), charge current in UC (I_{UC_ch1}), discharge current from UC (I_{UC_disch2}), fuel cell current before FC converter (I_{FC1}), fuel cell current after FC converter (I_{FC2}) and output signals are hydrogen and air flow values (*H2_SP, Air_SP*) and the reference of the DC/DC converter for switching (*FC_Conv, UC-ch_Conv, UC-disch_Conv*).

For each PEMFCs power sub-domain, if the load power required exceeds the available PEMFCs power, the difference will be supplied by discharging the UC, as long as it meets the SoC imposed restriction, namely to maintain it above 20%. The energy level stored in UC is considered sufficient to start the UC discharging as soon as SoC level reaches 50%. For 50% $\geq$ SoC $\geq$ 20%, the EMS commands the PEMFCs power to go to the upper level and to continue the UC charging.

If the set FC power level exceeds the load power needed, then the UC will be charged until it will become fully charged.

13.3.3 NI Labview Software Development for Control and Monitoring of PEMFCs/UC-HPS

Dedicated software has been developed in the NI Labview 2015 environment to control the test station operation and acquire experimental data. All DC/DC unidirectional converters (analog output and digital output) and mass flow controllers (hydrogen and air) are controlled by the software. The current, voltage and gas flow rates are measured. The software allows the visualization data in real time through a Graphical User Interface. All data is saved in a database at a frequency of 0.2 Hz. Figure 13.10 includes a screen shot of the test station software front panel along the location of the controls and indicators for each subsystem. The block diagram (Fig. 13.11) is a graphical representation of the monitoring and control software.

13.4 Experimental Results

Experimental tests were performed on a known load profile. This profile was implemented by programming an electronic load IT8518C (5 kW air cooled) profile consisting of 8 segments, which have been chosen so that, to have all cases the algorithm implemented EMS (Fig. 13.12). Thus, the segment 1 is the scroll for 15 s with a rated load of 1,200 W (zone 2 from the map efficiency FC); thereafter, accelerating the dP/dt 80 W/s variation power is passed in segment 2 (zone 2 + zone 3), segment 3 there for 45 s at a constant power of 2,400 W (zone 3), then is passed in segment 4 with ascension in ramp to 3,100 W for 35 s (zone 3 and 4), the segment 5 is 50 s at a power of 3,100 W (Zone 4), the segment 6 is a ramp 70 W/s. (Zone 4 and 5) for 10 s. At a power of 4,500 W until to the segment 7 (Zone 5), then is passed in segment 8, which consists of a brake of 20 s. until to the power load equals zero (here through all the zones). The ultracapacitor's initial charge status is 76%, which was calculated by measuring the voltage UC in real time and dividing it by 56 V, the maximum voltage of the UC.

The EMS algorithm was implemented in FPGA using method called "state machine". For the segment 1, the EMS algorithm determined PEMFCs to operate in Zone 2, fueling PEMFCs with H2 = 23.5 SLPM and Air = 91.6 SLPM providing power 2000 W. Excess power is directed by controlling the DC/DC converter charging in UC. When is passed in segment 2, PEMFCs remains to Zone 2 until the power load exceeds the threshold of 2000 W, then it passes into zone 3. In Segment 3 is observed as at a time, the ultracapacitor state of charge reaches 100%, at which point the routine is triggered, it passes in previous zone (Zone 2), the power difference to cover the load is made by controlling the discharge of DC/DC converter. The EMS algorithm passes through all segments correct profile, in the last segment when the load power goes under 1000 W to observe as PEMFCs remains in Zone 1 of operation so that the surplus power is charged in the ultracapacitor.

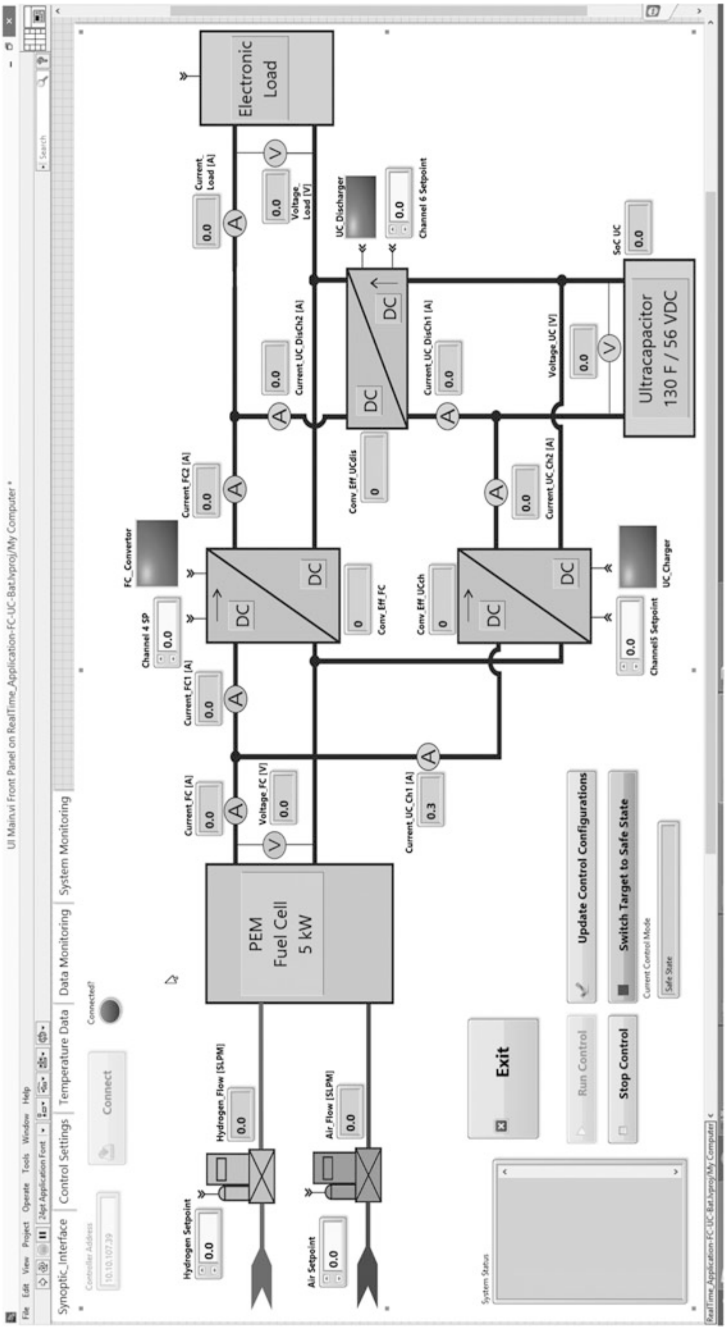

Fig. 13.10 GUI of the software to control the test station and acquire experimental data

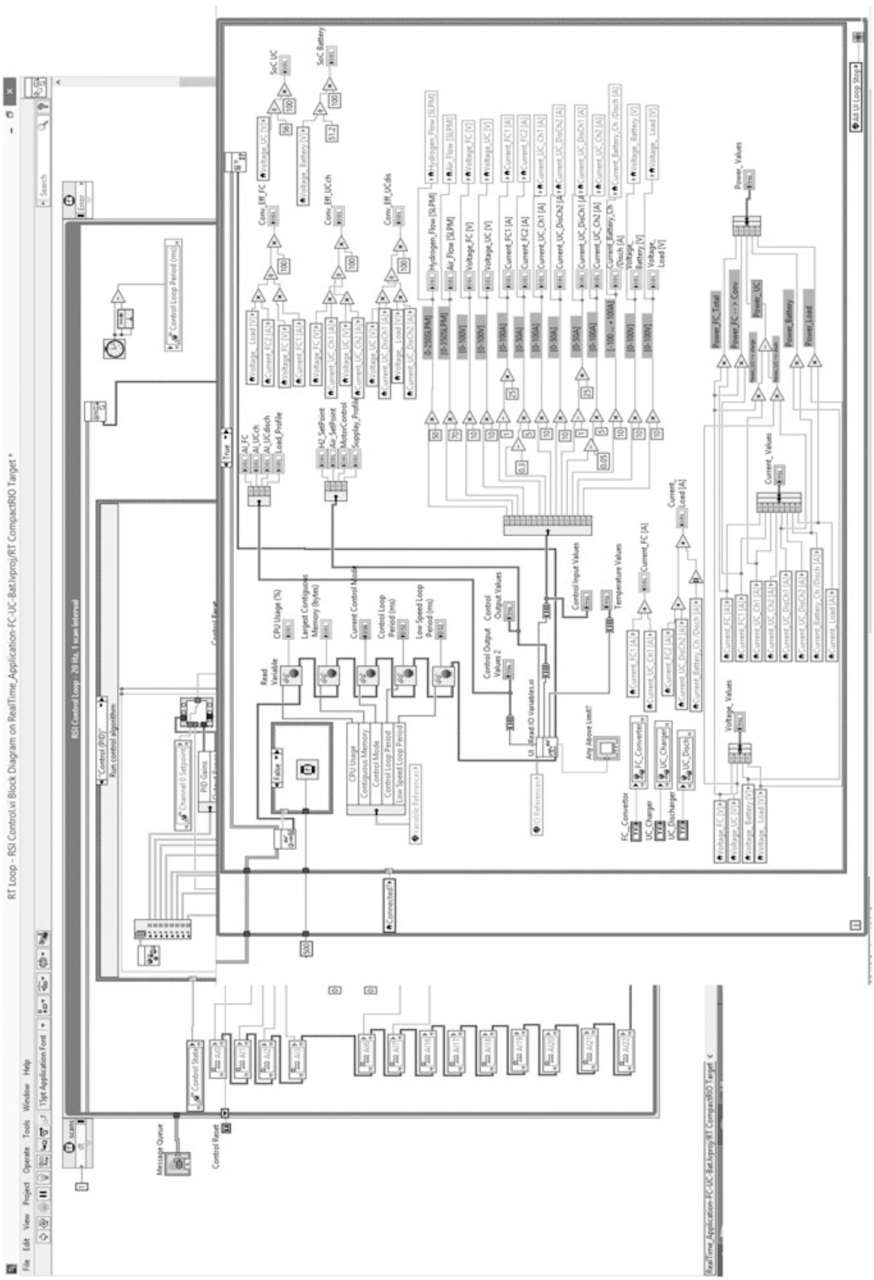

Fig. 13.11 Block diagram for control and monitoring

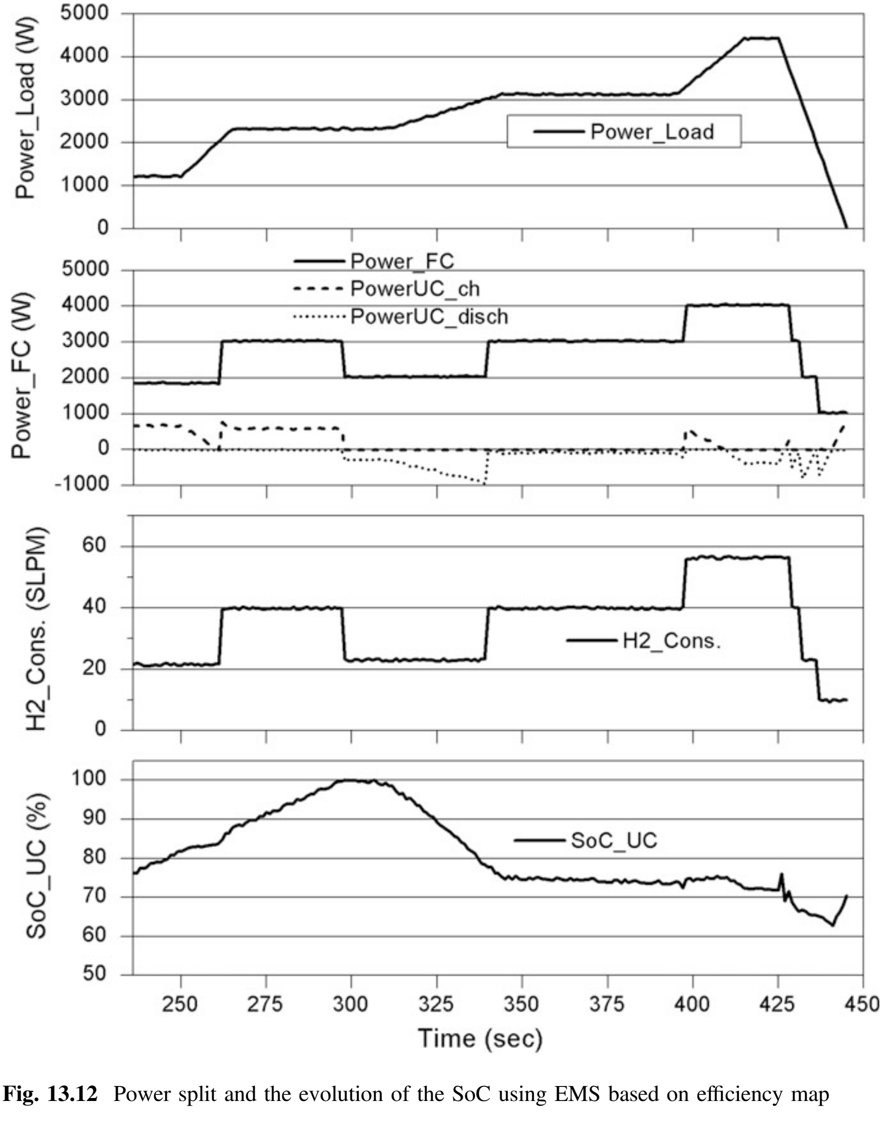

Fig. 13.12 Power split and the evolution of the SoC using EMS based on efficiency map

By using this algorithm EMS it has been observed that PEMFCs works on different levels in stationary conditions prolonging the life of FC. The ultracapacitor is protected for SoC less than 20%. Through the operation of PEMFCs at maximum efficiency on the level of operation has achieved a reduction in fuel consumption of 11.8%. Note that during load profile of 200 s the quantity of hydrogen consumed in FC/UC hybridized mode (with UC driven by EMS algorithm) and the pure mode (without UC) is of 1.05 and 1.18 g, respectively.

13.5 Conclusions

A new topology of HPS that consists in a PEM Fuel Cell stack (5 kW power) and a bank of ultracapacitors (130 F, 56 V, 57 Wh) was investigated in this chapter. It is used to meet the high power demand of the automotive applications, where the power demand fluctuates a lot. The PEMFCs operate in the flow-through mode fuelling and it is cooled with deionized water (65 °C). The stack is fed with humidified hydrogen and air, at a stoichiometry of 1.25 and 2 respectively and the gases are controlled by two mass flow controllers.

To protect the fuel cell against the power load fluctuations an EMS algorithm has been designed. This algorithm aims to direct the flow of power toward UC, when we have an excess of power from the PEMFCs, and vice versa, when the power produced by the PEMFC is not enough to take the power requirement from UC. The power flow is controlled using three DC/DC converters.

The EMS algorithm was based on an FC efficiency map and on the UC state of charge. This algorithm was implemented in a main routine and five subroutines. The main routine split the load power in five equal zones (1000 W per one zone). It is aimed that in each area the fuel cell to operate at the point of maximum efficiency. This algorithm was implemented in a Supervisory Control and Data Acquisition system that utilizes the NI CompactRIO That 9082 platform, software developed in the NI Labview 2015.

PEMFCs/UC HPS have been tested experimentally on a known load profile. The advantages of this new HPS topology are: extended lifetime of the PEMFCs by its operation in a stationary regime, protecting the state of UC Charge below 20% and reducing the consumption of hydrogen by 11.8% compared to a system without UC. This reduction in fuel consumption was due to PEMFCs operation in the areas with maximum efficiency.

Acknowledgements This work is supported by the Sectoral Operational Programme Human Resources Development (SOP HRD), financed from the European Social Fund and the Romanian Government under the contract number POSDRU/159/1.5/S/137390.

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