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Energy performance of a Fuel Cell hybrid system for rail vehicle propulsion

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Abstract

This paper focuses on the energy analysis of a rail vehicle in a real drive-cycle. The system includes a fuel cell, serving as the main engine, an energy storage system, composed of battery and supercapacitor, two DC/DC converters, both necessary for the connection with the electric motor, a regenerative brake, able to recover energy in deceleration, and a control system.

This hybrid system is obtained through a deep study of the available solutions which include the use of one or more energy sources to the selected drive cycle. Afterwards, the system sizing was made in order to achieve the expected performance with the most appropriate power levels, without oversizing or undersizing the powertrain. The components were selected on the market after appropriate calculations according to the task that each energy source performs.

After the identification of the components of the entire system, it is possible to perform an energy analysis. The fuel cell power is kept as constant as possible and it supplies the total energy demand; the battery provides the power variations at low frequencies while the supercapacitor provides those at high frequencies. The parameters analysed are: the current, the voltage and the power supplied from each energy source, the efficiency and the consumption of hydrogen for the fuel cell, the state of charge and the equivalent hydrogen consumption for the energy storage system.

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Keywords: : Hybrid powertrain, Fuel cell, Fuzzy Logic Control Strategy, Urban Railway.

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1. Introduction

The combustion of fossil fuels is one of the causes of climate change and environmental pollution and clean energy technologies are increasingly advancing in all the application areas involved. The transport sector is of fundamental importance in renewable energy research; innovation is necessary because transport is responsible for 17% of CO2 emissions every year [1] and, continuing in this way, emissions will exceed the limits imposed by governments.
Although the railway network is one of the most sustainable energetic and environmental means of transportation, only 30% is electrified and, even to a lesser extent, responsible for producing air pollutant emissions not at the point of use but in electricity production [2,3]. Among the possible energy sources, the fuel cell (FC) is a valid alternative. This electrochemical system is able to turn the chemical energy in input (contained in hydrogen) into electric energy with high efficiency and no emissions in loco. Unlike the other electrical systems, in this case, hydrogen is continuously fed into a tank with the advantage of a short refuelling time. Among the several types of FC, the Proton Exchange Membrane Fuel Cells are the most suitable for the transport sector due to their features: low operating temperatures, high efficiencies, high energy densities and low noise and pollution emissions [4].
The combination of railway and FC has been frequently researched. Almost all these studies analyse the hybrid powertrain where an energy storage system compensates for the slow power rate of the FC. In this way, the FC can work in steady-state operation, improving its efficiency and lifecycle, assisted by other energy sources. For instance, a Spanish team, in [5-8], have studied an FC – battery (B) tramway over the route of Sevilla Metro-Centro (Spain), with different control strategies. T. Ogawa et. al instead, in [9], conducted an energetic analysis of an FC-Supercapacitor (SC) powertrain by dynamic programming. Mathematical models of a hybrid system, composed of FC, battery and SC, with 2-FLC strategy, state machine structure and Equivalent consumption minimization strategy have been created by a Chinese group [10-12].
In this paper, a comparison of different hybrid systems is carried out; three configurations have been studied: FC-battery, FC-SC, FC-SC-B. The systems are tested on a real railway route and the energetic variables are compared in order to find the best configuration with low consumptions and high efficiencies.

Nomenclature

E_{acc}	Energy in acceleration [kWh]
E_{aux}	Energy auxiliary service [kWh]
E_{RB}	Energy recovered by regenerative brake [kWh]
E_{TOT}	Total energy of the drive-cycle [kWh]
SOC	State of charge [%]
P_B	Battery Power [kW]
P_{FC}	Fuel Cell Power [kW]
P_{RB}	Regenerative Brake Power [kW]
P_{SC}	Supercapacitor Power [kW]
P_{TOT}	Total power required by the drive-cycle [kW]
NH	Level of control strategy [-]
L	Level of control strategy [-]

2. Drive-cycle

The drive-cycle chosen is the LF-LRV tramway route in Samsun (Turkey), which links “Gar” station with “University” station [10], shown in Fig. 1, because of its power variations that allow the locomotive to be tested in different conditions. The energetic variables are illustrated in Table 1.

The auxiliary power is due to the air conditioning system consumptions, lighting etc., and it is constant and equal to 65 kW. The system is equipped with a regenerative brake to recover the deceleration energy which, otherwise, would be lost as heat. The power and the energy demanded by the cycle determine the sizing of the propulsion system components

Table 1. Driving cycle characteristics.

Maximum power	420 kW
Minimum power	-450 kW
Average power	85.2 kW
Auxiliary power	61 kW
Acceleration energy	8.09 kWh
Deceleration energy	4.8 kWh
Auxiliary energy	5.09 kWh

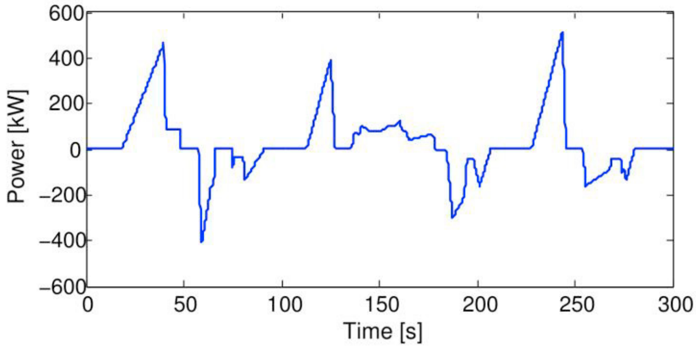

Fig. 1. Railway drive-cycle

3. Propulsion system

As already mentioned in the introduction, the target of this paper is to test three configurations of a fuel cell hybrid system in order to find the one that suits this application best.

Firstly, an analysis of the propulsive system features is carried out because there is no proper configuration for each application. The vehicle the authors chose is a train used for an urban route; this implies a lower power than an extra-urban train but a greater presence of different power variations, at high and low frequencies. Sudden variations might lead to rapid deterioration of the fuel cell; therefore, the authors analysed only hybrid systems without taking into account the use of a Full-FC powertrain.

The fuel cell is used to provide the total energy of the driving cycle; it is not determined by the system components and it is equal to eq. (1).

$$E_{TOT} = E_{acc} + E_{aux} - E_{RB} \tag{1}$$

The PEM selected is the 150 kW Ballard FCvelocity HD6, specifically designed for transport applications; its performance parameters are shown in Table 2 [11,13].

The FC is connected to the load through a unidirectional DC/DC boost converter in order to increase the output voltage and to protect the energy source against the high frequency power variation [14].

3.1. FC + Battery powertrain

The first configuration requires the use of a fuel cell and a battery (Fig. 2).

Lithium ion batteries are considered more suitable for transport applications than the other commonly used batteries because of their features: high energy, power density and long life-cycle. This battery must work in specific intervals of voltage and temperature (associated with the current) in order to avoid dangerous situations. Therefore, a Li-ion battery was chosen in this work [15].

A bidirectional boost/buck DC/DC converter was used to connect the battery to the load. This converter is necessary to allow charge (buck-mode) and discharge (boost-mode) operations, to keep the SOC in the preset intervals and to avoid premature damage [16].

The battery will, instead, deliver the remaining power required by the driving cycle, adding up to the one delivered by the FC, as in equation (2).

$$P_{TOT} = P_{FC} + P_B + P_{RB} \tag{2}$$

The battery selected is the Kokam-SLPB100216216H and its performance parameters [17] are shown in Table 3.

3.2. FC + Supercapacitor powertrain

In the second configuration, fuel cells and supercapacitors are used (Fig. 2).

Supercapacitors have high power density, with a larger electrode surface area than conventional electrolytic capacitors. They are used in many applications because of their high efficiency and long lifecycle although they have low energy density. Among SC, electric double-layer capacitors suit the transport applications thanks to the following features [18]:

- Large electrolytic area in contact;
- Good electrical conductivity;

Like the battery, the SC is connected to the load via bidirectional boost/buck DC/DC converter and the configuration system is shown in Fig. 2.

SC provides the power that the FC cannot supply since FC work remains unchanged, as in the previous case.

The SC selected is the Maxwell BMOD0063-P12 module 125 V, 63 F and its performance parameters [19] are shown in Table 4.

3.3. FC + B + SC powertrain

The third system is composed of FC, battery and SC (Fig. 2). It combines the features of each energy source: the battery has higher specific energy than the SC; by contrast, the SC has a higher specific power than the battery and it can provide energy for more charge/discharge cycles. For these reasons, the battery provides power at low frequency and SC at high frequency.

In this configuration, the battery is dimensioned to supply the energy needed to fill up the peaks while the SC is used to provide the required power. The recovered energy and the surplus provided by the FC charge the two components in the cycle stages with low or negative power requirements.

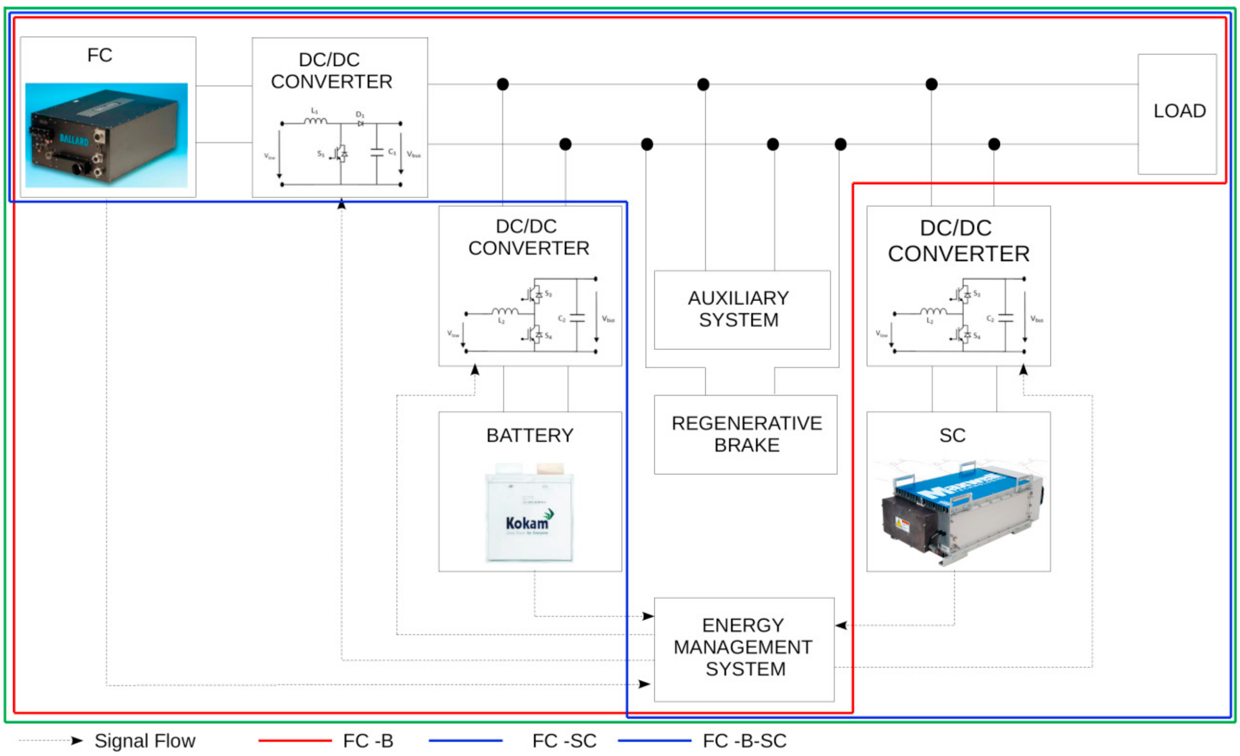

Fig. 2. Hybrid powertrains.

Table 2. Parameters of Ballard FC.

Performances parameters	Value
Gross power	150 kW
Weight	404 kg
Operative temperature	330 K
Cell number	762
Nominal hydrogen pressure	2.24 bar
Nominal air pressure	2.06 bar
Nominal efficiency	0.55
Nominal air mass flow	0.061 m^3/s

Table 3. Parameters of Kokam battery.

Performances parameters	Value
Capacity	40 Ah
Weight	1.1 kg
Nominal Voltage	3.7 V
Cell number	108
Discharge current cont	8 C
Discharge current peak	10 C
Max charging current	2 C
Cut-off Voltage	2.7 V
Maximum Voltage	4.2 V

Table 4. Parameters of Maxwell SC.

Performances parameters	Value
Rated capacitance	63 F
Rated voltage	125 V
Maximum current	1900 A
Number of cells	48
Specific energy	2.3 Wh/kg
Usable specific power	1.7 kW/kg
Mass	61 kg

4. Energy management system

The control strategy plays a primary role in the hybrid system; this enables the amount of needed power from each energy source to be achieved in order to extend the average life-cycle of the sources and to obtain high efficiencies. Control strategies can use two different mathematical models and they are divided into two groups: rule-based and optimization-based controllers.
The controller is a Fuzzy Logic Control, a rule-based strategy, selected thanks to its main features [20]:

- high adaptability to different types of hybrid vehicles in various power conditions;
- maximum customization allowing a total control of the vehicle, based on human experience;
- nonlinear relationship between multi-input and multi-output properly characterized;
- chance to work with not very precise data.

The signal control is elaborated through IF – THEN rules as:

If (P_{TOT} is NH) and (SOC is L) then (P_{FC} is 2)

Triangular or trapezoidal functions divide each variable domain. In Fig. 3, only some variables are illustrated due to reasons of concision.

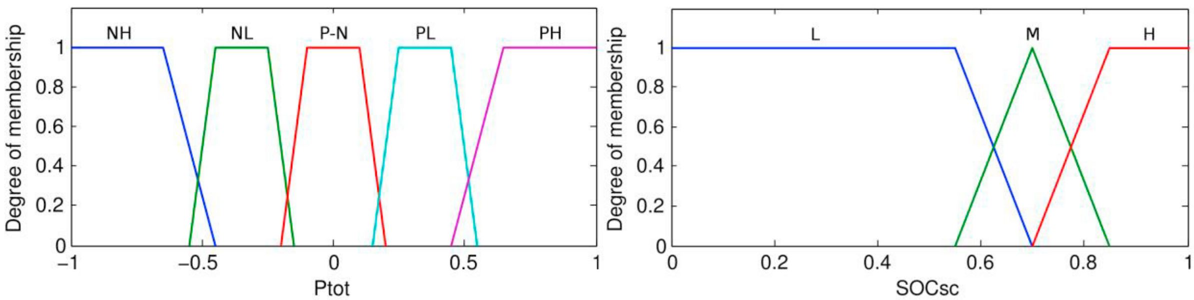

Fig. 3. FLC rules.

5. Results

The three hybrid systems composed of FC-battery-SCs and FLC strategy were tested for the real drive cycle of Samsun, Turkey. The power required is illustrated in Fig. 1 and the main energetic variables in Table 1, as above mentioned. In the following section the results obtained from the analysis of each configuration are discussed.

- *FC-B results*

Analysis led to a choice of battery sizing with 120 cells in series and 4 in parallel. For the sake of brevity, only meaningful variables trends are illustrated. Fig. 4 shows the FC and battery outputs. The FLC system tries to keep the power required by the FC constant. Moreover, when high accelerations occur, the FC power increases in order to satisfy the power demand. In negative power zones, the FC must reduce its outputs in order not to exceed the maximum absorbable current of the battery. For these reasons, there are marked power ratings affecting efficiency and consumption. The FC power is in a range between 20 and 140 kW. The efficiency mean value is 45.5%, as illustrated in Fig. 4 and the hybrid system consumes 0.53 kg of hydrogen. The voltage and current limits of the battery are respected, keeping the variables at predetermined intervals, (425 V-465 V) and (-315 A-1015 A). The battery power lies in a large interval, between -150 kW and 450 kW, instead the SOC range is narrow (68.5-70.5). This may imply a battery oversizing; but, the power required for the drive-cycle, supplied by the battery, almost reaches the permitted limit (current limit), because of the FC size. Therefore, the battery power is suitable, while accumulating energy is excessive, as shown in the SOC trend.

- *FC-SC results*

The SC size is obtained with 5 modules in series and 4 in parallel. As in the previous case, the FC power is set between 50 kW and 130 kW with some sudden changes that reduce the FC efficiency (Fig. 5); in this way, the SOC is kept in the predetermined range (30-90). The voltage and current remain within the recommended limits. However, the current remains far below the limit; the powertrain does not take advantage of high power density, owing to low energy density. The maximum SC output power, calculated from the datasheet, is much higher than the one essentially delivered. The FC-SC powertrain may result oversized, as with the FC-B system; but, in fact, the SOC ranges within the limits imposed by the FLC, the energy is delivered in the right proportions.

- *FC-B-SC results*

The Energy storage system (ESS) components sizing of the last configuration is 100 batteries in series and 5 SCs in series. Compared to the previous cases, the FC power assumes a steadier trend with no sudden variations, as shown in Fig. 6. During acceleration, the SC provides the peak power while the battery supplies the basic energy. The voltage and current safety limits are respected for each component. Unlike the previous cases, there is no excessive difference between the amount to be delivered and the delivered one: the SC power is comparable to the datasheet values and the battery SOC lies in a reasonable range, as shown in Fig.6. This one illustrates the FC efficiency that is fundamentally constant with a mean value of 48%.

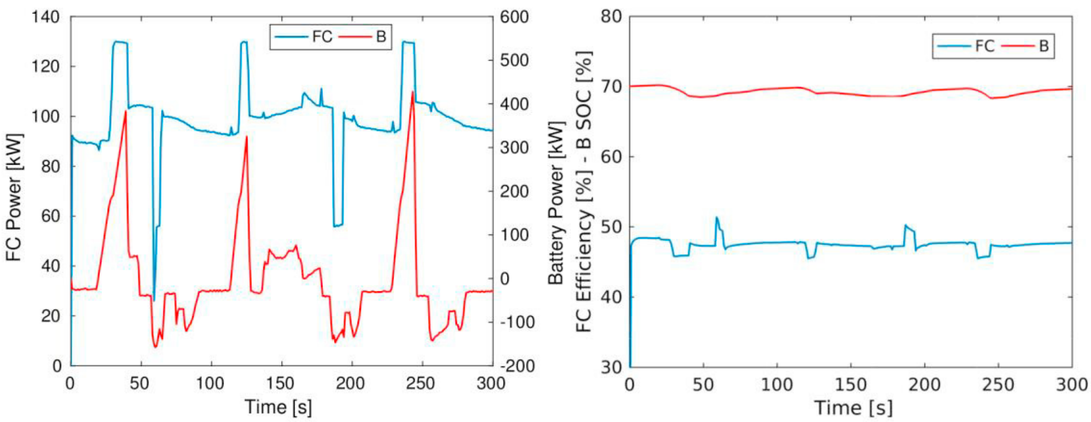

Fig. 4. Output of FC - B powertrain.

After separate analysis of the powertrain, a comparison is carried out, shown in Table 5. The FC-B-SC powertrain achieves higher efficiency and less hydrogen consumption for FC, mainly due to the lower power variations, improving the FC lifecycle. Regarding the battery, the energy delivered from the two configurations does not differ substantially, although the battery number is four times higher in the FC-B system; in fact, in this system, the SOC range is narrow hence the battery capacity in not fully exploited. Regarding the SC, the maximum supplied currents are quite similar in the comparison powertrains, but in the FC-SC case there are 4 modules in parallel instead of 1, resulting in an increase in the system weight.

The data analysis confirms that the FC-B-SC powertrain exhibits the best performance, as it was foreseeable.

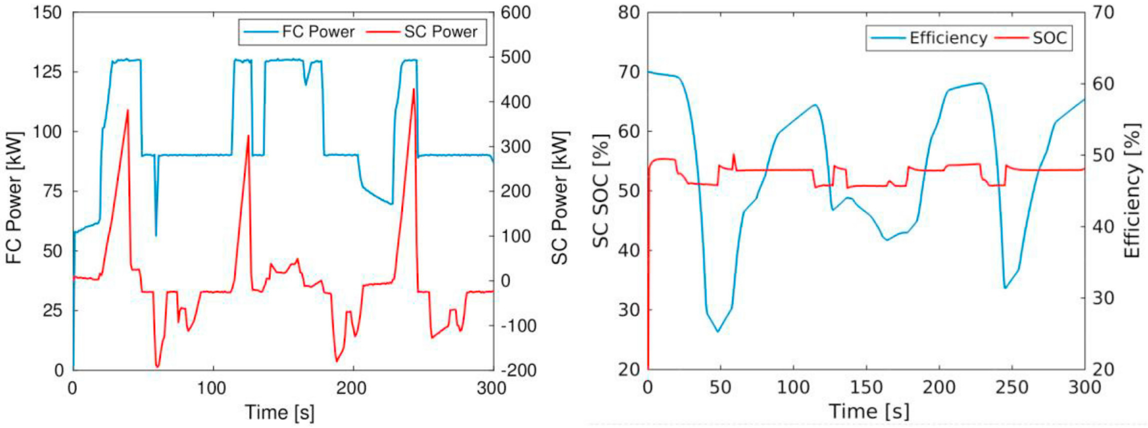

Fig. 5. Output of FC - SC powertrain.

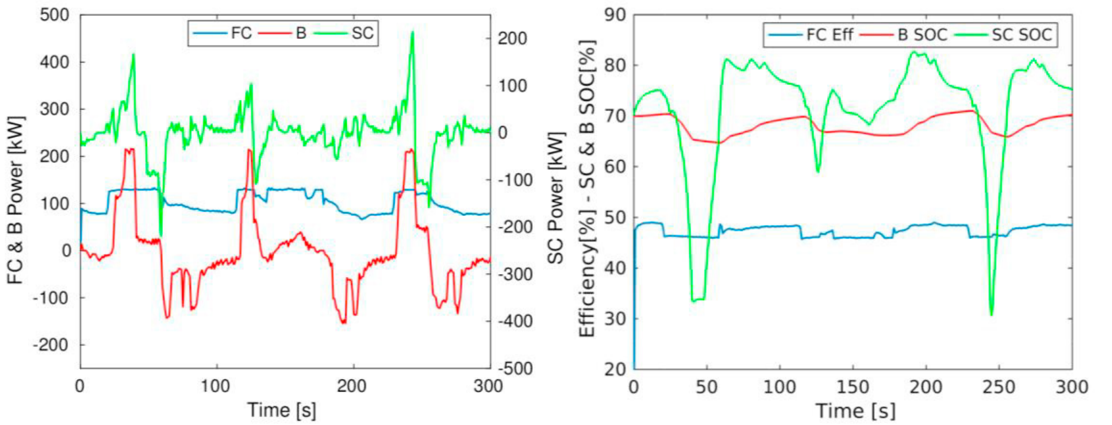

Fig. 6. Output of FC - B - SC powertrain.

Table 5. Performance comparison.

Performance parameters	FC-B	FC-SC	FC-B-SC
FC Efficiency [%]	45.5	47	48
Hydrogen consumption [kg]	0.53	0.52	0.51
Number of batteries	120S x 4P	-	100S x 1P
Number of SCs	-	5S x 4P	5S x 1P
Battery SOC	68.5-70.5	-	64-71
SC SOC	-	30-90	30-85

6. Conclusion

In this paper, three different hybrid powertrains composed of FC, battery and/or supercapacitor, were compared on a real urban railway drive-cycle. An FLC system manages the powers of each energy source in order to achieve high performances and low consumption and take advantage of the components features. As resulting from the analyses, the best solution for this application is the FC-B-SC system. The FC supplies the energy needed for the cycle, the SC fills the power peaks and the battery provides the additional energy in acceleration.

By using this configuration, the efficiency reaches a mean value of 48%, better than those of the other configurations, and the hydrogen consumption is 0.51 kg.

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