ISSN 1827-6660
Vol. 14 N. 4
July – August 2019

International Review of Electrical Engineering (IREE)

Contents:

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International Review of Electrical Engineering (IREE)

The ***International Review of Electrical Engineering (IREE)*** is a publication of the **Praise Worthy Prize S.r.l.**.
The Review is published bimonthly, appearing on the last day of February, April, June, August, October, December.

Published and Printed in Italy by **Praise Worthy Prize S.r.l.,** Naples, August 31, 2019.

Praise Worthy Prize

International Review of Electrical Engineering (I.R.E.E.), Vol. 14, N. 4
ISSN 1827- 6660 July – August 2019

Modeling, Analysis and Implementation of an Urban Electric Light-Rail Train Hydrogen Powered

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Abstract – *A novel hydrogen power configuration of a Light Hybrid Electric (LHE) rail train able to operate along sub-urban non-electrified rail lines is proposed and analysed in the paper. The electric motors of the emission-free LHE rail train are fed by a hybrid power unit consisting of hydrogen fuel cell stacks and a set of high-speed kinetic energy storage systems. A control strategy of the power-train components has been developed to manage power flows in order to reduce the fuel consumption. This advanced and environment friendly hybrid propulsion system offers the opportunity to increase the power-train efficiency so that the fuel consumption is minimised. Simulator software of the proposed HLE rail train has been implemented in order to design the power-train components and compute train performance. A rail transport service is considered and a round trip journey of the LHE rail train is simulated over an existing re-designed not electrified single track line in the sub-urban area of L'Aquila city (Italy). Furthermore, the specific fuel consumption comparative analysis between the hydrogen rail train and a diesel one running over the selected path in the same operating conditions has been performed and the results are discussed in terms of CO_2 emissions too. The results show that the proposed LHE rail train is technically suitable and advantage to operate in urban environment.*

***Keywords**: Hybrid Light-Rail Train, Hydrogen Fuel Cell, Flywheel Energy Storage System, Urban Rail System, Emission Free Transport System*

Nomenclature

a	Acceleration of the rail train
g	Acceleration of gravity
m	Gross mass (rail train and passengers mass)
m_{ax}	Mass on each axle of rail bogie
m_t	Rail train mass
n	Number of rail cars per train
r_w	Radius of rail train wheel
v	Speed of the rail train
C_A	Drag coefficient
K_A	Auxiliary services power rate
K_r	Transmission ratio
N_p	Rail train carrying capacity (passengers)
R_A	Air resistance
R_S	Slope resistance
R_W	Rolling resistance
S	Vehicle frontal area
T	Traction thrust
α	Rotational mass inertial coefficient
β	Angle of the track slope
η_{fc}	Fuel cell efficiency
η_t	Transmission efficiency
η_M	Electromechanical conversion efficiency of the traction drive (converter and motor)
ω	Angular speed of the flywheel
$\omega_{\max}$ ($n_{\max}$)	Maximum angular speed of the flywheel
$\omega_{\min}$ ($n_{\min}$)	Minimum angular speed of the flywheel

I. Introduction

Traditionally, the rail transport system is conceived and designed to operate using electrical or diesel energy sources. Electric traction power requires expensive infrastructure that are economically justified only in the "main" railway lines where a high crossing flows (passengers and goods) occur. For instance, in the European Union (EU) context, the British and Italian rail networks are only 34% and 70% electrified, respectively [1]. The EU average value of non-electrified railway lines is 46.29% [2]. The low traffic density lines, mostly single track, are usually served by diesel trains as their electrification business case is almost unfavorable. This kind of lines, representing a considerable part of the EU railway network, often connects both small-medium towns and sub-urban areas. Usually the diesel rolling stock has a considerable age; the most recent Italian version is EURO 3 certified [3]. Consequently, the diesel trains traffic contributes to generate local emissions (carbon oxides, nitrogen oxides and particular matter) and high noise levels that mostly negatively affect urban environment. The transport sector accounts for nearly a fourth of all greenhouse gas emissions in Europe; the current average share of renewable energy in transport fuel consumption is 7.10% [4]. The European Commission policy strategy aims to achieve the target of a 60% reduction of CO_2 emissions from transport sector by 2050 through a gradual decarburization of the transport sector. In this scenario, research and innovation are key elements to progress in this area. Vehicles powered by clean energy carriers can play a key role for realizing a carbon free transport system able to reduce drastically greenhouse gas emissions [5]. Hydrogen combined with fuel cell (FC) technology has become very attractive for emission free traction systems and has opened up new opportunities in railway passenger transport too. A FC is an electrochemical device that directly produces electric energy by combining hydrogen and oxygen (from air) with a catalyst; a small amount of clean warm water and steam are produced during operation. The hydrogen fuel can be produced from natural gas (reforming) or by water electrolysis. In the latter case, free emission traction energy can be achieved by using electric energy generated from renewable sources. The principal advantages of a hydrogen powered rail train compared to a diesel one are pollution free operation, electric traction, braking energy recovery and low noise level. On the contrary, the main disadvantages refer to high cost of FCs, low level of consumer acceptance and lack of the hydrogen refueling infrastructures (just over 120 fueling stations are active in the EU) [6]. On this regard, the EU Commission has already elaborated a strategy to promote the hydrogen utilization and distribution for vehicle traction purposes [7]. Although these current limits, hydrogen technologies costs are expected to drop significantly in the next years.

Several basic research activities, tests and successful services experiences have been carried out on the use of hydrogen FCs in rail transportation [4], [8]-[19]. As an example of urban application, a first hydrogen powered three-cars tram with electrical traction drives is operating in China [20]. For regional service applications, trains powered by hydrogen FC have been tested by Railway Technical Research Institute in Japan [21]. The Coradia iLint has started a passenger service in Lower Saxony, Germany. The two pre-series trains, homologated by the German Federal Railway Association in July, are now running between the cities of Cuxhaven, Bremerhaven, Bremervörde and Buxtehude [22]. The above-mentioned systems have dispelled any doubts on the technical and technological aspects and have paved the way for the extensive use of hydrogen vehicles also in the field of the railway system in the next future. All the above-mentioned hydrogen powered systems combine the use of FCs and electrochemical batteries to feed the traction motors. With the aim to avoid on-board electrochemical batteries for traction, a Light Hybrid Electric (LHE) rail train fed by a novel Hybrid Power unit (HPU) combining hydrogen FCs and a set of flywheel energy storage system (FESS) has been proposed by researchers of University of L'Aquila [23]. Although the energy is stored in kinetic form, the FESS can be seen as a system that delivers and stores electrical energy given that the energy exchange is based on electromechanical devices.

High speed (up to 100,000 rpm) FESSs require: i) high-performance rotor materials to maximize the specific energy density; ii) magnetic bearings and vacuum vessel to decrease friction and windage losses.

They have much higher specific power density, lower full cycle life cost than electrochemical batteries, low maintenance cost and minimal environmental impact. For these reasons FESSs represent one of the high-tech and green alternative technologies to electrochemical batteries in case of short charge-discharge cycles (less than ten minutes) when the higher auto discharge rate of the FESS has a minor impact on the efficiency of the cycle [24]-[33].

In transportation systems the on-board FESS can support different applications such as railcars, urban buses [34]-[36], locomotives [37]-[38] and electric city trains [39]-[42]. Compared to the previous configuration of the LHE system, the paper introduces the following new features: i) an updated HPU design for feeding both rail train traction motors and auxiliary devices and ii) a control strategy implementation for fuel consumption reduction avoiding dissipative devices on-board (e.g. rheostats). Moreover, the proposed urban LHE rail train operating along an existing non-electrified railway is modelled and analyzed.

Section II of the paper illustrates the rail vehicle and the power train architecture. Electrical power system and control logic are presented in Section III. Mathematical models are illustrated in Section IV. Case study and system performance analysis are illustrated in Section V.

Fuel consumption, energy balance and CO_2 emission saving are presented in Section VI. The concluding remarks are in Section VII.

II. Rail Vehicle Architecture

A scheme of the proposed LHE rail train architecture is shown in Fig. 1; it consists of two side rail cars and a towed wagon. The traction motors are placed in the two end side trolleys; the FC and the hydrogen vessels are equally distributed on the roof of the two side rail cars.

For each rail car, the proposed power plant uses an electric traction motor (EM) fed by a HPU consisting of a FC stack and a FESS set. An electrochemical battery (AB) is exclusively used to feed the auxiliary devices (AS) on board of the train by means of the auxiliary power bus (continuous blue line).

The traction motor, the FESS and the auxiliary battery are connected to the DC power bus (continuous red line) by means of Traction Motor Converter (CM), Flywheel Converter (CFESS) and Auxiliaries Battery Converter (CAB) to manage the power flows as required by the master control system (CS) via a communication bus (green line).

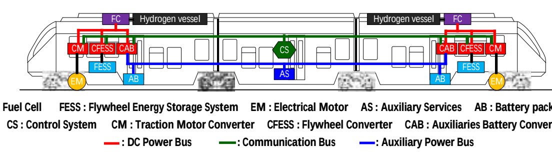


Fig. 1. Scheme of the LHE rail train

Given that the master control imposes a constant set point for the FC power because of its slow dynamic response, the FESS must be able to handles the load variations: it provides power when the load power is higher than the FC power, it recovers when the FC power is higher than the load power and during the regenerative electrical braking.

III. Electrical Power System and Control Strategy

The electrical power architecture was carried out according to the concept system design illustrated in Fig. 1 of the previous section. The power flow of the single drive, illustrated in Fig. 2, consists of the following components:

(1) A DC/AC converter and its controller (CM) to supply the traction motor;
(2) A FC stack operating at constant power;
(3) A FESS and its controller (CFESS) to manage the transient power;
(4) A buffer battery pack (AB) connected to the DC bus of the auxiliary loads.

The FC is directly connected to the DC bus working at constant voltage (600 V) except during turn-around times when the train is not running. The FESS system is connected to the bus via a bidirectional AC/DC converter, while the battery is connected to the DC bus via a DC/DC converter.

While the battery-connected DC/DC converter manages the power flow in one direction, the FESS interfacing AC/DC converter is a bidirectional power converter. The main task of the master controller (CS) is to impose the constant DC bus voltage and, therefore, to control the power flows of the above-mentioned converters. The master controller inputs to keep constant bus voltage are:

- The battery state of charge (SOC);
- The flywheel speed of the FESS;
- The value of the bus voltage.

Therefore, the master control provides the power flow references to the converter controllers; then the power flows are imposed by means of the single converters.

The auxiliary services on board include the cooling and heating circuits, the low voltage power line for the electrical drives, etc.

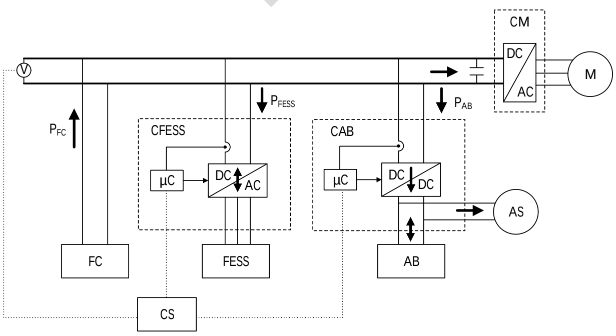


Fig. 2. Power flow of the electrical system

In the proposed power flow chart, the auxiliary services are fed by the battery pack system and by the DC bus by means of the CAB. The onboard auxiliary services power has been considered constant. In standard operating condition the battery SOC is controlled to be between 0.5 and 0.8 in order to be able to both store and supply energy most of the time. The new control strategy was developed with the aim to i) increase efficiency of the vehicle by a new hybrid propulsion system and reducing train mass; ii) avoid energy dissipation devices on board; iii) overcome the chemical batteries for traction. Moreover, the control strategy imposes constant value of the DC bus voltage by managing the FESS power (P_{FESS}) and the battery power (P_{AB}) flows on the base of the following instantaneous power balance:

$$P_{FC}(t) = P_{FESS}(t) + P_U(t) + P_{AB}(t) \tag{1}$$

If the DC bus voltage is higher than the set point value, then the master controller decides where to address the power flow on the base of the FESS energy status and on the miss balance between the FC (P_{FC}) and the HPU (P_U) powers defined as:

$$\Delta P(t) = P_{FC}(t) - P_U(t) - K_A \cdot P_{AUX}(t) \tag{2}$$

where $K_A \cdot P_{AUX}(t)$ is the auxiliary services power supplied by the FC. As illustrated in the flow chart of Fig. 3, the bus voltage control strategy is based on the following three points:

- $\Delta P(t) > 0$ and $\omega(t) < \omega_{max}$ the controller (CS) addresses the $\Delta P(t)$ flow to the FESS by acting on the corresponding AC/DC converter (CFESS);
- $\Delta P(t) > 0$ and $\omega(t) = \omega_{max}$ the controller (CS) addresses the $\Delta P(t)$ flow to the auxiliary battery system by acting on the corresponding AC/DC converter (CAB);
- $\Delta P(t) < 0$ and $\omega(t) > \omega_{min}$ the controller (CS) takes the $\Delta P(t)$ flow from the FESS by acting on the corresponding AC/DC converter (CFESS).

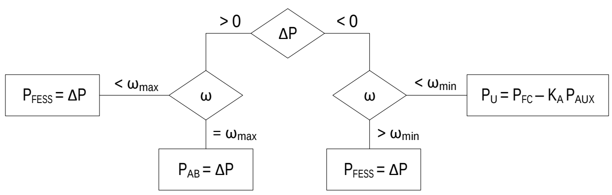


Fig. 3. Flow chart of the DC bus voltage control strategy

IV. Models

In order to simulate the rail train performance, the mathematical models of both LHE train and HPU components have been developed as shown below.

IV.1. Vehicle model

The single rail train simulator software, developed by using open source software Scilab [43], was used for the investigation. It allows the rail vehicle to be simulated on a defined path by varying the system parameters. The simulator solves the rail vehicle equation of motion by numeric integration of the relation (3):

$$T(t) = m \cdot \alpha \cdot a(t) + \left[R_w(t) \pm R_S(t) + R_A(t)\right] \quad (3)$$

$$R_W = \left[0.7 + \frac{130}{m_{ax} \cdot g} + 0.009 \cdot v\right] \cdot m \cdot g \cdot \cos(\beta) \quad (4)$$

$$R_S = m \cdot g \cdot \sin(\beta) \quad (5)$$

$$R_A = 0.0473 \cdot C_A \cdot S \cdot v^2 + (n-1) \cdot \left(0.0716 \cdot v^2\right) \quad (6)$$

where v is the train speed. As relations (4) and (6) are empirical formulations, speed is in kilometers per hour, mass in ton and resistance in Newton. Considering regenerative electrical braking too, the electrical traction power P_u is evaluated as:

$$\begin{cases} P_u(t) = \dfrac{T(t) \cdot v(t)}{\eta_M \cdot \eta_M} & \text{if } T(t) \cdot v(t) > 0 \\ P_u(t) = \eta_M \cdot \eta_M \cdot T(t) \cdot v(t) & \text{if } T(t) \cdot v(t) < 0 \end{cases} \quad (7)$$

The electric traction motor is simply modelled by means of its torque and power capability, i.e. the torque/speed and power/speed limit curves.

IV.2. HPU Model

The HPU is modelled by considering the following FC and FESS sub-models.

IV.2.1. Fuel Cell Model

The FC is modeled using the electrical work of a FC, considered as a reversible system as described in [44].

The FC model is based on the current and efficiency experimental characteristics as function of the output power of a proton exchange membrane (PEM) FC with low operating temperatures (60-80 °C) that is suitable for applications on mobile systems [45]-[49]. Since the FC operates at constant power, its working point is chosen close to maximum efficiency. Therefore, a FC constant efficiency (η_{fc}) is assumed in the model.

IV.2.2. FESS Model

Concerning the FESS model, the amount of useful energy can be calculated as:

$$\Delta E_K = \frac{1}{2} J \left(\omega_{max}^2 - \omega_{min}^2\right) = \frac{1}{2} m_f r^2 k \left(\omega_{max}^2 - \omega_{min}^2\right) \quad (8)$$

where J is the moment of inertia of the rotor, m_f is the rotor mass, r is the rotor radius, k is the inertial constant which depends on the rotor shape. The FESS power losses (P_L) are taken into account by the relation (9):

$$P_L = \delta \cdot E_K \quad (9)$$

where δ is a constant and its value is computed so that the stored kinetic energy is reduced by 15% in one hour.

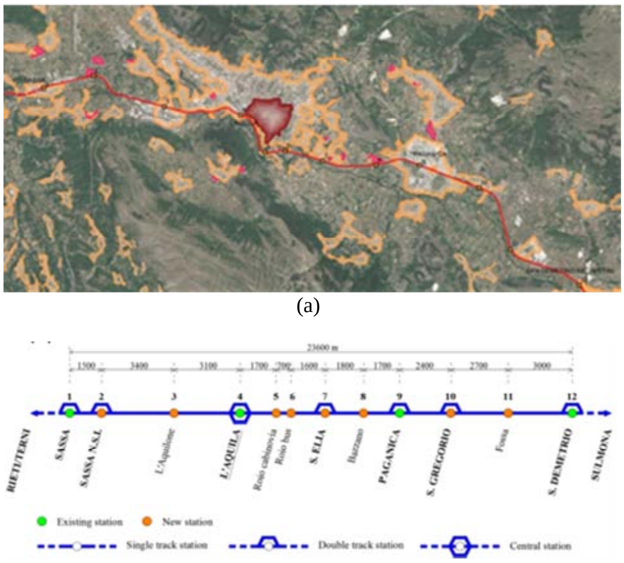
V. Case of Study

The existing non-electrified single-track route (23.6 km long with four stations) in the sub-urban territory of L'Aquila city (Italy) has been selected for study application. This railway section is a part of the regional line that connects L'Aquila to the cities of Rieti (at West) and Sulmona (at South-East).

The current service is operated by diesel rail trains at very low average frequency (about 1 train per hour). Figs. 4 show the map and the scheme of the considered railway route. In order to improve the system accessibility further eight new stations (orange points) have been added to the four existing double tracked stations (green points).

Moreover, three of the new stations are double tracked to increase the service frequency up to four trains/hour/direction. The rail train service is simulated on the route from S. Demetrio to Sassa stations and return.

The elevation difference between Sassa and S. Demetrio stations is about 80 m; the maximum and the average slope values of the railway route are 13 ‰ and 3.38 ‰, respectively. Fig. 5 and Fig. 6 illustrate the roundtrip slope profile and the horizontal radius of curvature of the considered railway route. The duty cycle assumptions and the rail train design data are reported in the following sections.



(a) (b)

Figs. 4. Railway: (a) route map (b) route scheme

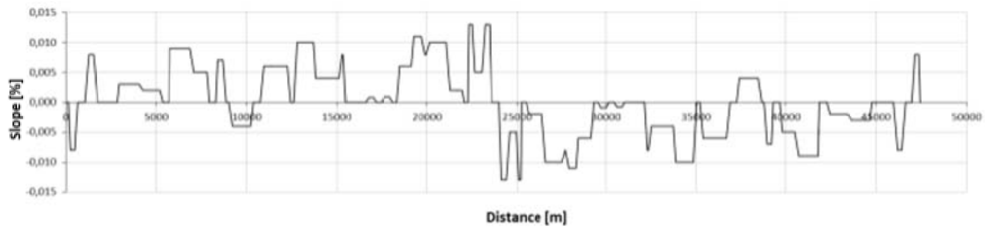


Fig. 5. Slope of the rail track section

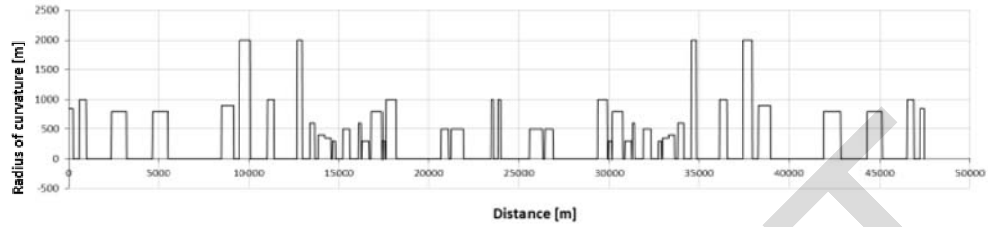
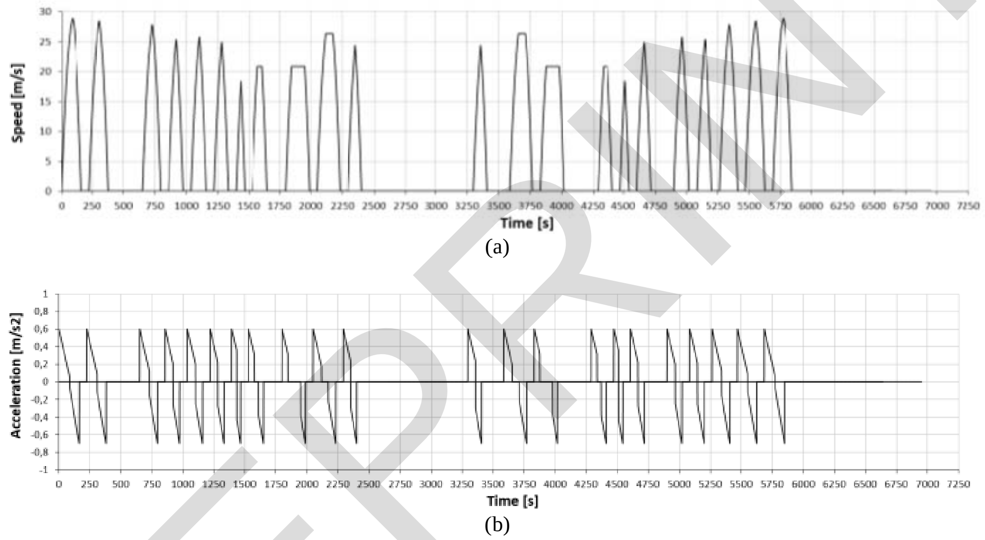


Fig. 6. Railway section radius of curvature



Figs. 7. Driving cycle, (a) speed versus time)b) acceleration versus time

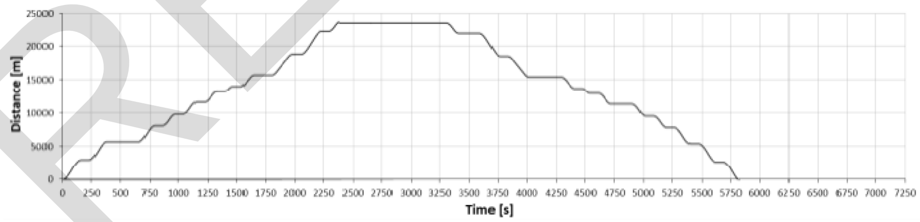


Fig. 8. The roundtrip distance-time graph

V.1. Duty Cycle Characteristics

The roundtrip (47.2 km long) from S. Demetrio to Sassa stations has been considered as duty cycle.

Fig. 7 illustrates the speed and acceleration profiles of the rail train that have been theoretically computed by taking into account the following parameters: max speed of 22 m/s; max acceleration/deceleration of 0.6 m/s^2, average dwell time at stations of 60 s; turn-around times at S. Demetrio and Sassa railheads of 25 min and 15 min, respectively. The different value of the two turn-around times is due to the operating needs of the line. The roundtrip time is about 115 min as illustrated in the distance-time graph of Fig. 8.

V.2. Rail Vehicle Characteristics

The selected LHE rail train configuration is bidirectional and it is based on 3 cars, two of those are motorized. The main data of the considered LHE rail train are listed in Table I.

TABLE I
MAIN DATA OF THE LHE TRAIN

	Symbol	Unit	
Number of wagons	n	-	3
Number of rail cars	N_{rc}	-	2
Carrying capacity (passengers)	N_p	-	215
Rail train mass	m_t	t	58
Gross mass @ full load	m	t	73.05
Axle mass	m_{ax}	t	9.2
Wide	W	m	2.65
Length	L	m	37.61
Front Area	S	m^2	9.8
Drag coefficient	C_A	-	0.45
Max motor power	P_{max}	kW	400
Max motor torque	C_{max}	Nm	1600
Efficiency of traction drive (motor/generator)	η_M	-	0.965
Transmission efficiency	η_t	-	0.93
Transmission ratio	K_r	-	4.8
Rotational mass inertial coefficient	α	-	1.18
Radius of wheel	r_w	m	0.425

V.3. Simulation and Results

The rail vehicle model and the design data illustrated in the previous section are used to simulate the LHE train running over the selected railway path by imposing the duty cycle conditions.

The simulation has been performed by assuming:

- A full load condition;
- A constant power of 100 kW required for the auxiliary services;
- The battery system must be able to feed the auxiliary services for half an hour;
- The FC power value is reduced at 53% during the turn-around times;
- The auxiliary services power rate (K_A) is 0.5;
- The starting battery and FESS state of charge are set almost to the highest limits (80% and 95%);

The FC stack characteristics (Fig. 9) have been evaluated by starting from experimental data of a single PEM fuel cell [48]. Given that the FC efficiency characteristic is almost flat, the working point has been chosen in order to minimize the number of the FC stack.

At maximum power (P_{max}) of 95 kW for each stack, the current (I_{mp}) and voltage (V_{mp}) are 160 A and 600 V.

In effect, the lower efficiency could be compensated by the reduced weight on board. Based on the above considerations, a FC constant efficiency (η_{fc}) of about 0.6 is conservatively assumed.

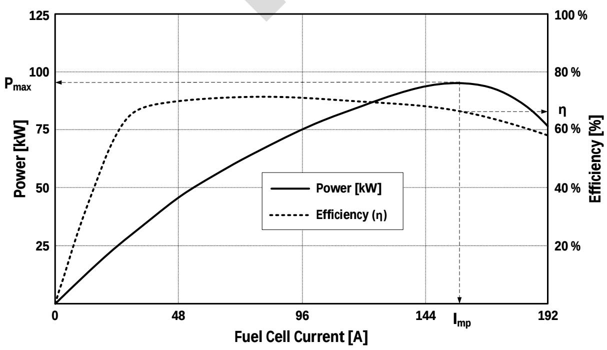


Fig. 9. Fuel cell characteristics

Fig. 10 shows the limit characteristics (maximum power and torque) of the electrical traction motors considered in this study; each induction motor can deliver 400 kW and almost 1600 Nm as maximum values of power and torque. As shown in Table II, where the main data of the HPU components are listed, the train needs two HPUs, each of them consists of one FC stack, four FESSs and one auxiliary battery pack. According to the data design, each auxiliary battery stack mass is 1166 kg by assuming lead-acid battery with 30 Wh/kg. The electrical power of the traction motors, FC stack and FESS are shown in Fig. 11. The graphs highlight that the FC stack provides a constant power of 190 kW except during the turn-around times when the FC stack power (100 kW) is shared by the auxiliary systems and the FESS. On the contrary, the FESS handles the transient loads. Fig. 12 and Fig. 13 illustrate the power and the state of charge (SOC) of the auxiliary battery pack during the duty cycle.

Fig. 14 shows the flywheel rotational speed of FESS that varies between 15,000 and 60,000 rpm. Fig. 15 shows the energy of the power-plant components. The results of this analysis clearly show that the auxiliary devices energy represents a significant part of the energy consumption because the auxiliary devices require energy during the round-trip times too.

TABLE II
MAIN DATA OF HPU COMPONENTS

	#		Symbol	Unit	
FESS	2	Rotor mass	m_r	kg	27.72
		Rotor radius	r	m	0.13
		Rotor inertial moment	J	kgm^2	0.36
		Charge/discharge efficiency	η_f	-	0.9
		Rotor speed	n_{min}-n_{max}	rpm	15,000-60,000
		Useful storage energy	E_{max}	MJ	6.66
		Peak power	P_F	kW	100
FC	2	Efficiency	η_{fc}	-	0.6
		Power	P_{FC}	kW	95
Battery	3	Capacity	C_B	kWh	35
		Voltage	V_B	V	420
		Mass	M_B	kg	1166

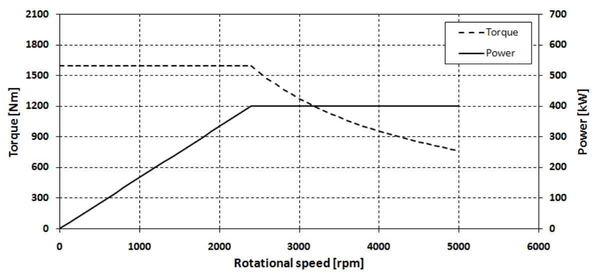


Fig. 10. Torque and power limits of the motor

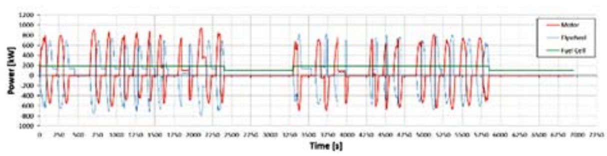


Fig. 11. Electrical power of traction motors, FC stack and FESS

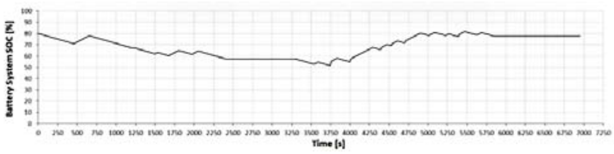


Fig. 12. Power of auxiliary battery pack

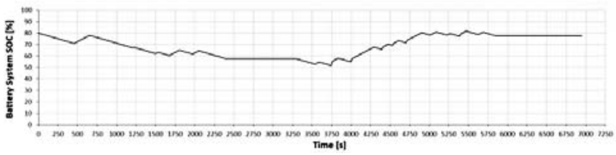


Fig. 13. Auxiliary battery pack SOC

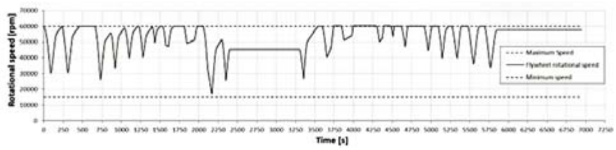


Fig. 14. Flywheel rotational speed of FESS

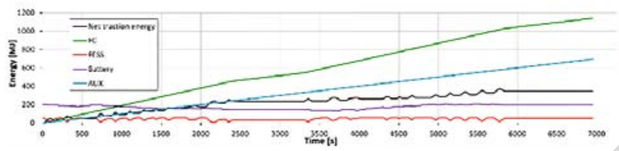


Fig. 15. Energy graphs of power-plant components

For the round-trip duty cycle, the following results are obtained:

- Energy generated by the FC stack: 1140 MJ;
- Traction energy: 822.4 MJ;
- Recovered energy: 481.7 MJ;
- Net traction energy (equal to 822.4-481.7): 340.7 MJ;
- Auxiliary devices energy: 695.0 MJ.

VI. Consumption and Emission Analysis

In this paragraph the hydrogen consumption is estimated for a single round-trip journey over the considered rail path. The hydrogen consumption of the rail train is calculated using the following relation:

$$m_{H2} = \frac{E_e}{\eta_{fc} \cdot H_i} \left[\text{kg}\right] \tag{10}$$

where E_e (MJ) is the FC electrical energy and H_i (119.9 MJ/kg) is the hydrogen's lower heating. Taking into account the energy consumption value (1140 MJ) and neglecting the small difference between the initial and final state of charge of both battery pack and FESS set, the LHE rail train round-trip hydrogen consumption (mH_2) is 15.85 kg, corresponding to a specific consumption of 1.56 gH_2 per passenger per kilometer (Table III); it has been computed by dividing the hydrogen consumption by the length of the round-trip length and by the maximum number of passenger on-board.

According to these calculation results, 111 kg of hydrogen are required to achieve an autonomy of seven round trip journey, corresponding to about 14 h of the train operation. Considering pressurized metal tanks at 350 bar to store fuel, a set of 4 cylindrical tanks (0.30 m of inner diameter and 7.5 m of length) must be installed on board (4 tanks for each rail car). A fuel consumption and carbon emission comparative analysis were performed by considering the LHE train and a similar diesel train in the same operating conditions. The "Minuetto" three cars diesel train (110 t of mass, 286 passengers of carrying capacity and 2x560 kW of peak power) has been considered as benchmark; its average fuel consumption is 1.83 kg/km with carbon emission factor of 3.175 kg/kg diesel [50]. The results of comparison are illustrated in Table IV. It should be noted that the LHE rail train allows a 20.3 gCO_2/passenger/km local emission to be saved with a clear environmental benefit. Consequently, about 6.7 $kgCO_2$/passenger are saved for a rail train daily travel of 330 km (about 7 round trips). Moreover, if the hydrogen is produced by means of clean energies there is no polluting emission at all.

TABLE III
ROUND TRIP JOURNEY TRAIN CONSUMPTIONS

Energy (E_e)	Hydrogen		
(MJ)	(m^3)	(kg)	(g H_2/pass/km)
1140.3	1.30	15.85	1.56

TABLE IV
ROUND TRIP JOURNEY TRAIN CONSUMPTIONS (COMPARATIVE ANALYSIS)

LHE train		Diesel train	
H_2	CO_2 emission	Diesel fuel	CO_2 emission
(gH_2/pass/ km)	(gCO_2/pass/ km)	(g_{diesel}/pass/ km)	(gCO_2/pass/ km)
1.56	-	6.4	20.3

VII. Conclusion

A novel light hybrid electric rail train powered by hydrogen fuel cell and a set of high-speed flywheel energy storage systems has been illustrated in the paper.

The control strategies of the power-train components and a numerical model have been developed to manage the power flows in order to minimize the fuel consumption.

As application study, the light rail train has been simulated to operate over an existing rail path corresponding to one-track line section (23.6 km) in the sub-urban territory of L'Aquila city. The following achievements have been obtained: i) low fuel consumption; ii) no need of energy dissipative devices on board; iii) about 21% energy saving achieved by means of the regenerative braking; iv) no chemical batteries for traction; v) no local emission; vi) no global polluting emission if the hydrogen is produced by means of clean energies. The results indicate that the proposed rail train configuration with the adopted control strategy allows a low fuel consumption (1.56 g H_2/passenger/km) to be achieved and a 20.3 g CO_2/passenger/km of local emission to be saved respect to a diesel rail train. In conclusion, numerical results indicate that the proposed rail train hydrogen fueled is technically suitable for operation on the urban selected railway line. Next research step will focus on the developing of the power plant adaptive logic control based on the path and service requirements in order to further reduce the rail train fuel consumption.

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1827-6660(201907/08)14:4;1-D