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Development and realization of a hydrogen range extender hybrid city bus

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HIGHLIGHTS

- To increase the range of the vehicle a range extender powertrain configuration was chosen.
- The powertrain is composed by a FC system, Zebra batteries and an AC induction motor.
- The control strategy adopted allows to assure the functionality of the vehicle.

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ABSTRACT

Electric vehicles, equipped with electrochemical batteries, are expected to significantly penetrate the automotive market in the next few years. Though, the recharge time for battery pack and the autonomy range can constitute a limit. An appropriate use of fuel cell technology in electric vehicles can now represent an advantageous choice both from a technical and economic point of view.

This paper reports the results of the development of a hybrid electric city bus, performed by the synergy between fuel cell and batteries. A pure electric city bus, equipped with eight Zebra batteries, was acquired and modified in a fuel cell and batteries hybrid vehicle. In the final version the bus was equipped with six batteries and a hydrogen plant with a proton exchange membrane fuel cell system. In particular an innovative powertrain management, where even the time required for the terminal stops is used to charge the batteries by the fuel cell, is described. Set-up tests on the fuel cell system acquired are presented. Further, tests were conducted also on the battery pack working on board in a real route to demonstrate the capability of the reduced battery pack to drive the vehicle.

1. Introduction

The swift growth of the global population is concentrating in urban areas, determining an increasing consumption of energy due to cities. Given that, specific energy policies related to urban areas are already foreseen with the aim at reducing energy consumption, increasing energy efficiency and mitigating the CO_2 emissions. In this contest, mobility and transportation can be considered one of the key elements to achieve these targets. Furthermore, long term petrol price increases and climate changes have created in the automotive industry a new competitive market based on the spread of more sustainable technologies.

Several automotive manufacturers have promoted interest in full electric vehicles (EVs) and hybrid vehicles (HVs) because both types of means of transportation could be run comparable with traditional fuelled vehicles but are more cheaper to maintain and environmentally friendly [1–3]. Given that, the urban mobility is a key issue to improve the life quality of people, to increase market opportunities, and to achieve a more sustainable transportation of goods and people [4,5].

The actual early market is based on the commercialization of HVs provided with internal combustion engine (ICE) and electric motors supplied by batteries. Battery, depending on the rate of power of the electric motor with respect the ICE, is used for regenerative breaking and for the traction at low speed (urban centres). This approach allows reducing the fuel consumption and CO_2 emissions, but does not avoid the presence of hydrocarbons. The pure EVs, that do not present any ICE in the powertrain, due to their limited autonomy range, are expected to cover the market segment of city cars and city buses [6]. Nowadays, hydrogen technologies are considered too expensive both for the costs of fuel cell systems (FCS) and hydrogen. Further the life time (40,000 h) of the FCS has to be improved.

Within an Italian national project, CNR-ITAE is involved in the development of a hybrid electric city bus, composed by the hybridization between fuel cell and batteries able to overcome the

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limits of individual technologies through the synergy of the two systems [7]. The final prototype aims to demonstrate that an appropriate use of fuel cells in electric vehicles can perform, yet now, a real competitive product, above all if employed in vehicles fleets.

2. Background

A pure electric city bus was acquired and converted in a fuel cell hybrid city bus.

The project targets are reported below:

- increasing the overall autonomy (+30%) respect the electric version
- keeping low the cost of investment through the use of a reduced size of fuel cell system
- minimizing the time for the batteries recharge
- keeping the initial number of passengers and the same weight

To achieve these goals, a range extender powertrain configuration was chosen. The FCS through the DC/DC step up converter works in parallel with battery pack, and both supply energy to the DC side of the motor inverter [8]. The principal energy source is the battery pack. The FCS, working at constant power, pushes the State of Charge (SoC) of the batteries during the bus stops, but is used also during the traction.

The vehicle selected for the prototype realization is a city bus (Model Alè Elettrico, Rampini Carlo SPA) of 44 passengers capacity and a AC drive motor of 85 kW (rated power) with regenerative breaking system (Fig. 1).

A preliminary design and dimensioning were carried out on the basis of energy aspects using simulation models developed in Simulink environment and more details can be found in Ref. [9].

The optimal level of hybridization was evaluated as reported in Refs. [9], and consists of a low power fuel cell system and 6 Zebra batteries [10–14]. The PEM system, installed on the roof of the bus, is fed by hydrogen stored in 2 tanks (Dynetec, compressed at 200 bar) containing about 4.8 kg of hydrogen each [15]. With this configuration the project targets can be achieved. The comparison of the capital cost between the only-battery version and the hybrid one is 15% more, considering the reduced battery pack and the additional costs due to the whole hydrogen plant. So, the hybrid version cost is a little bit more than the only battery version.

Fuel cost prediction needs to take into account the targets for the next years of hydrogen prices and the way to produce (from natural gas or from renewables), to store and distribute it in the future. Cost analysis has to consider several aspects from now to the next 10–20 years: hydrogen infrastructures spread, large scale use, improvement and cost reduction of hydrogen technologies [16]. Considering the target of 3,5 \$ kg^{-1} [17], the cost prediction for this vehicle, due to hydrogen, should be about 33 \$ per day.

Fig. 1. Hybrid city bus developed.

This range-extender configuration proposed can now:

- reduce the number of vehicles needed in an electric buses fleet management, thanks to the fast refueling due to the hydrogen and to the extended autonomy
- facilitate the creation of a hydrogen vehicles early market thanks to the lower investment cost, compared with the full power one (total fuel cell vehicle)

Taking in to account that the hydrogen pressure in this bus was set at 200 bar (the available hydrogen refueling is @ max 250 bar), other additional advantages (more autonomy) due to an enhanced fuel compression (350 bar), could be obtained by the same powertrain, without a vehicle weight growth.

3. Powertrain management

3.1. Electrical architecture

The powertrain (Fig. 2) is composed by:

- Six ZEBRA batteries (Model Z5-557-ML3X-38 – FZSonick, Rated Energy: 21.1 kWh, OCV: 557 V, Efficiency: 90%), divided in two sub battery packs of three batteries each one. The first was installed inside the city bus, the second in the rear.
- A fuel cell system (Model PFV005 Nuvera Fuel Cells, Nominal Power: 5 kW, 40 cells in series, Efficiency: 55%) positioned on the roof of the bus jointly the hydrogen storage systems (design developed by SOL).
- A DC/DC step-up converter developed during the project by STMicroelectronics (Nominal Power: 6 kW, Efficiency: 89%).
- The previous traction section, represented in Fig. 2 by the AC induction motor (Model 1PV5138-4WS24, Siemens) and the 3 phases inverter (Model DC-DC/IGBT MONO Inverter, Siemens).

In Fig. 2 the scheme reports also the connections with the auxiliary services section, where a DC/DC Step-down converter allows recharging the 24 V aux battery and supplying the services during the traction. When the ZEBRA traction batteries are not already activated, the 24 V aux battery performs the switching-on

Table 1
City bus configuration.

Parameter	Unit	Value
Bus weight	kg	10904
Bus dimensions	mm	7570 × 2200 × 3120
Bus n_{seats}	–	44
Bus electrical engine	kW	85
Bus Vnom, DC	V	650
Bus Vop, DC	V	300–750
Fuel cell system power	kW	5.6
Fuel cell system output voltage	V	27–40
Fuel cell DC–DC converter voltage (nominal)	V	$36_{down} - 600_{up}$
Fuel cell DC–DC converter power (nominal)	kW	6
Cylinder volume	l	150
Number of cylinders	–	2
Cylinders pressure	bar	200
Hydrogen mass	kg	4.89
Single battery energy	kWh	21,2
Single battery power	kW	30
Number of batteries	–	6