Modelling of a range extender power train for a city bus

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ABSTRACT

The *H-BUS* is a joint project of National Research Council of Italy and two supplier companies to develop a range extender Fuel Cell/Battery Hybrid Electric city bus.

Within the project, CNR TAE Institute is involved in determining the optimal level of hybridization assessing all boundary conditions (mission, performances, hydrogen consuption, range, etc...). The paper reports the characterization results of the hybrid system which allowed the identification of the power and energy consumption. These data were the starting points to define the size of Batteries and Fuel Cell (FC) system and to optimize the batteries State of Charge (SoC). PEM (Polymer Electrolyte Membrane) and ZEBRA® (Zero Emission Battery Research Activities) technologies have been selected for the fuel cell system and batteries, respectively.

Keywords: HEV, range extender, PEM, ZEBRA®, modelling

1 INTRODUCTION

Sustainable mobility is one of the main political strategy of European Union (UE) devised to reach a greenhouse gas level compatible with European target: 20% less than actual value of CO_2 into 2020. In the last decades, a changes in favour of the private transport is occurred. Serious consequences are strictly related in terms of environmental impact. In order to follow the European political direction, different actions started both in terms of new urban mobility and innovative power train solutions. Besides these actions, the basis for sustainable mobility is mainly the use of low/zero emissions vehicles.

The advantages and disadvantages of Electric Vehicles (EVs) are generally known and accepted. EVs help the environment by eliminating exhaust emissions and reducing dependence on fossil fuels. However, the disadvantages of limited range, increased vehicle weight and too long batteries charging time (6-8 hours) limit their use in commercial applications. Hybrid Electric Vehicle (HEV) proposed in this project intends to solve above mentioned problems regarding pure battery Electric Vehicles. Hydrogen is considered the optimal replacement of fossil fuels, particularly in the transportation sector which represents the major oil-consuming sector in the world. Buses offer greater opportunity than cars in terms of weight and volume because they can more easily contain the fuel cell stack, balance of plant, fuel storage system, and electrical energy storage devices. In literature several papers concerning fuel cell EVs are reported. In particular the state of the art describes mainly prototypes of bus in total fuel cell configuration with stack size of 100-250 kW [1-5]; this means high cost and a consequent no favour introduction to the market. Combining fuel cells with batteries it is possible to achive the best compromise between the two technologies.

The aim of *H-BUS* project is to realize a pre-commercial Fuel Cell/Battery HEV able to increase the range (at least 30%) with respect to same bus in a standard electric configuration, using a small size of fuel cell that works as batteries recharge on board.

2 RANGE EXTENDER CONFIGURATION

A range-extender HEV is essentially an EV with an on-board charging system [6]. In the proposed configuration FC system works as batteries recharge that provides, following an identified strategy, the necessary power to the driving cycle to increase the autonomy of the vehicle. The storage system (traction batteries) provides, however, the energy required to satisfy the peak power demand.

The bus selected for the prototype realization is an electric vehicle having an 85 kW rated power of electric drive motor and a capacity of 44 passengers (Fig.1). The same city bus was previously tested in pure battery EV configuration equipped with 8 ZEBRA batteries and a 70 kW electric drive motor.

Figure 1: City Bus

In the proposed solution the electrochemical batteries are connected in parallel to the FC system (Fig.2).

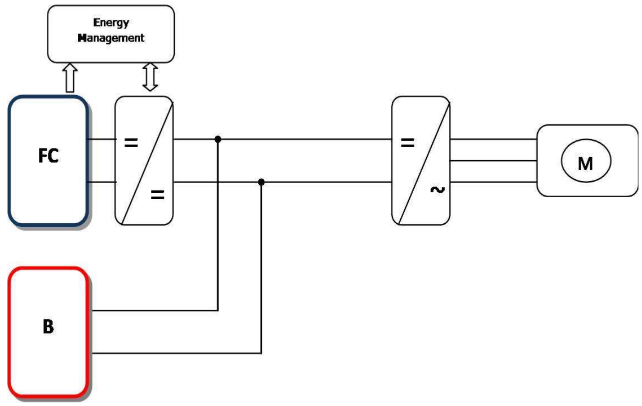

Figure 2: Block diagram of the combined system

In order to maximize energy efficiency and to preserve the FC system from continuous changes in the operating point, that could reduce its lifetime, FC system operates at constant power every time the boundary conditions allow it.

The DC/DC converter allows the control of the maximum input current, fixing the nominal operating point of the FC system and thus setting the maximum power expressed by the device ($P_{FC\text{-Ref}}$). When electric motor request is greater than $P_{FC\text{-Ref}}$ (startup/normal driving/acceleration) energy gap is filled from batteries.

If the power required by the electric motor should be less than the reference power $P_{FC\text{-Ref}}$ (low load/deceleration/braking/bus stop), the FC system allows the charge of the batteries.

2.1 FC System

The chosen FC system is a Nuvera Fuel Cells product composed by a PEM FC based on XDS-900 stack and the linked ancillaries: a blower for the air, a pump for the water and a fan for the cooling circuit. Dedicated micro–computer and software drive the entire system for operations and safety.

The stack is based on self-humidifying technology, so the water circuit works both for cooling and humidification. As well known, a Fuel Cells, like batteries, convert the energy contained into chemical fuels into DC power through electrochemical reactions.

Differently from batteries, Fuel Cells are fed with an external source, like hydrogen stored as compressed gas. Depending on the size of the cells, active area and number of cells, stack voltage could be variable, so, in order to reach the expected voltage a DC/DC converter is needed.

The PEM FC system, that will be installed on the bus, will be fed by hydrogen stored in 2 tanks (compressed at 200bar) containing about 4,8 kg of hydrogen each.

2.2 Battery

Batteries used in HEV/EV must have specific features regarding their capability in regular discharge. In particular batteries have to able to deliver full power even with deep discharge in order to ensure long range. After a thorough comparison between different storage technologies available on the market, FZ SoNick ZEBRA® battery has been selected as the one most responsive to the requirements of the project. The characteristics of this type of battery, in fact, make it an excellent solution both for HEV and for EV, particularly in terms of energy density.

A typical ZEBRA® module [7] exhibits an energy density of 120Wh/kg which is 3-4 times higher than conventional lead-acid batteries and 2-3 times higher than nickel-metal hydride batteries [8]. The selected model is the ***Z5-557-ML3X-38*** (216 cells, Rated Energy: 21.2 kWh) shown in Fig.3.

Figure 3: FZ SoNick *Z5-557-ML3X-38*

2.3 Preliminary sizing of power train

Preliminary energy analysis, carried out by estimating the energy autonomy of the bus in range-extender configuration, shows that a suitable size may be:

- From 5 to 8 ZEBRA® batteries having a total rated energy range of 110÷170 kWh;
- 1 FCS with a power range of 5÷10 kW.

3 ELECTRIC POWER TRAIN MODEL

The research process for hybrid systems can be simplified by utilizing computer simulations to identify the most favorable vehicle configuration in specified operating conditions. In this paper, simulation studies have been performed to evaluate the potential SoC saving and autonomy increase with respect of pure battery EV bus. The simulation models have been developed in the Matlab® Simulink® environment utilizing the SimPowerSystems tool (Fig.4).

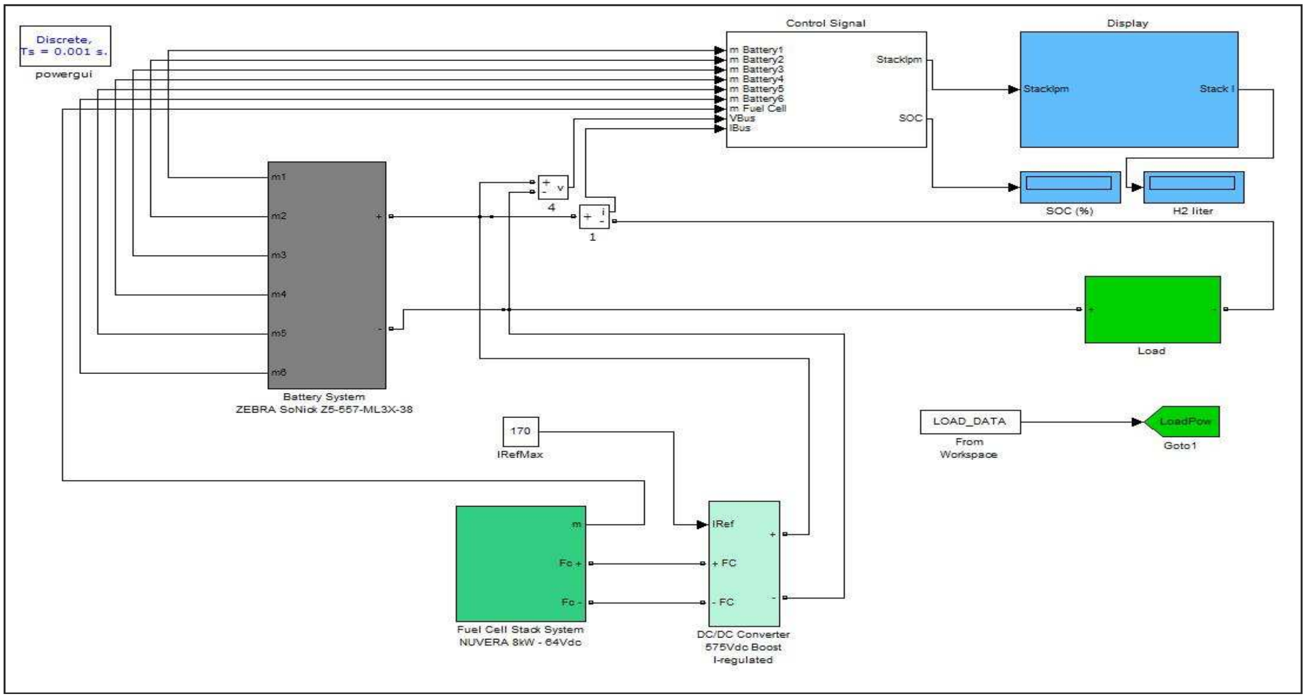

Figure 4: Simulink® model of the powertrain

The FC system operates at constant power and it is connected to the dc-bus (370÷670 Vdc) via DC/DC step-up that converts the stack voltage into the fixed value for batteries recharging. The battery pack is connected in parallel on the same dc-bus. The model acquires all the system parameters and shows the SoC (%) status and hydrogen consumption (liters). In Fig.5 is reported the battery model discharge characteristics at different current values.

Figs 6 and 7 show the polarization curves of the stack models of 5kW and 8kW, respectively (Power Flow conditions). The current limit of the DC/DC converter has been set to 170A, corresponding to 29.85Vdc and 47.8Vdc for the FC system of 5kW and 8kW respectively.

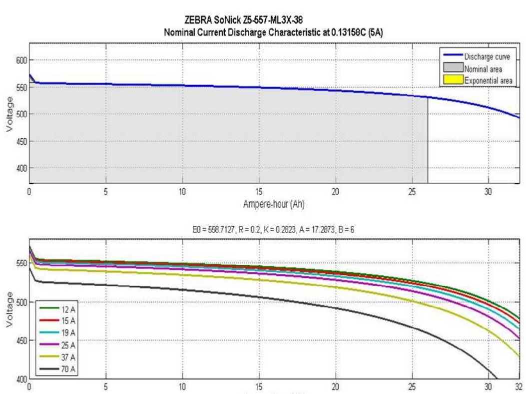

Figure 5: *Z5-557-38-ML3X* discharge

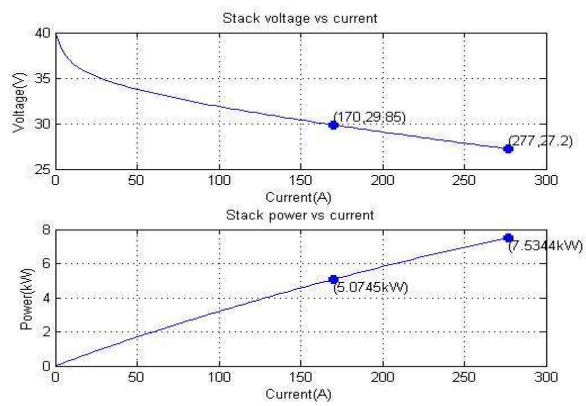

Figure 6: 5kW PEM FC stack model. Polarization curves

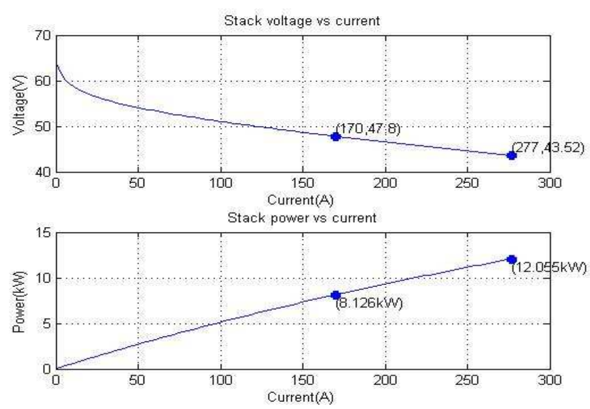

Figure 7: 8kW PEM FC stack model. Polarization curves

A real urban cycle has been implemented in the model and used for the comparison of different power train configurations (Fig.8). These data have been measured on the CAN-bus of the same city bus equipped with 8 ZEBRA® batteries and Ansaldo electric drive motor (70 kW). The simulation time is 45900 sec. (12hr 45 min) equivalent to the bus route.

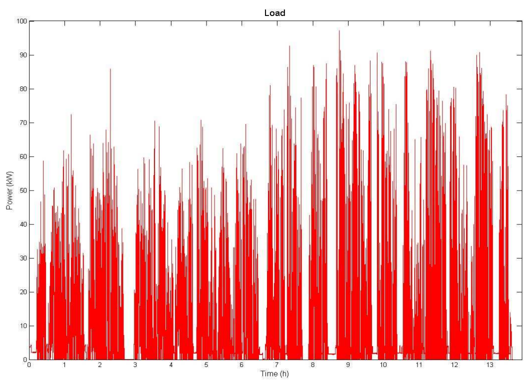

Figure 8: Load profile

4 RESULTS

A number of models with different sizes of PEM FC system and batteries have been tested. With the aim to obtain a comparative analysis on the increasing autonomy of the explained range extender configuration, with respect to the EV configuration, two consecutive cycles have been implemented. The SoC limit has been fixed to 20%.

The power train with 6 ZEBRA® batteries connected with 5 kW FC system appears as the best solution. With the same final SoC value the new configuration allows to increase the range of about 40% as shown in Tab.1 and Fig.8.

The obtained results show that Fuel Cells and Batteries achieve an optimal synergy because their combination provides better performance and lower costs than batteries or total fuel cells vehicles. A basic premise remains the possibility of implementing appropriate control policies through the use of power converters.

The project provides the development of a DC/DC converter customized for the specific application; moreover, in order to manage all power sources (batteries, fuel cell, hydrogen) and their interface with electric motor a tailored electronic power control unit will be developed.

Power Train Configuration	**Final SoC (%)**	**H_2 (lt)**	**Hours**
8 ZEBRA® Batteries	20	-	12h 45min.
6 ZEBRA® Batteries + 5 kW FCS	20	45438	18h 10min.

Table 1: Simulation results

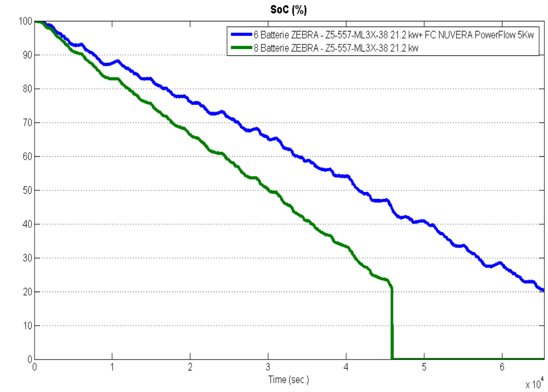

Figure 8: SoC (%) analysis. Comparison of proposed HEV (blue) and pure battery EV (green)

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