Intelligent Powertrain Management System for a Fuel Cell Electric Vehicle

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Abstract: FAAM Group S.p.A. is located in Monterubbiano (AP) - Marche - Italy and it is one of the largest companies in its area. Its core business is the production of industrial batteries (motive power and standby) as well as ecological vehicles for OEMs, public institutions and the private users. Hydrogen vehicles are the most efficient and less pollution vehicle respect to the standard solutions (Gasoline and Diesel Vehicles) and for this reason, FAAM Group, in collaboration with the Univesità Politecnica delle Marche, has transformed its standard Electric Vehicle (*Smile* vehicle) in a Fuel Cell Electric Vehicle. The use of different control laws, PID controllers, PID Fuzzy gain scheduling and Fuzzy controllers are developed to optimize the fuel consumption for a given path. Simulation results and real data provided that, using the same architecture and a smarter control law, it is possible to reduce the fuel consumption and to increase the efficient of the whole system.

1. INTRODUCTION

The increasing cost of fuel as well as pollution problems are motivating the scientific community to look for new solutions to minimize fuel consumption and the production of polluting gases. In this scenario, Fuel Cell Electric Vehicles can combine the high efficiently of a fuel cell with the absence of the production of pollution gases (Li [2006]). Fuel cells are electrochemical systems able to convert chemical energy of a combustible material, as hydrogen, directly in electrical energy without the need of a thermal component. These systems area characterized by an higher performance of energy conversion compared to conventional thermal systems (Li [2006]). Total efficiency levels are around 50%, meaning that the electrical energy produced per unit of fuel used costs half of what thermal systems can provide. Fuel Cell Electric Vehicles use hydrogen as primary source to provide the mean power request; a battery pack is used as a power buffer with the aim to provide peaks during high power requests.
In this paper the power system of *Smile* H_2 is introduced and analyzed. *Smile* H_2 is a four-wheeler vehicle with a maximum ground weight of $1.100Kg$, a top speed of $50km/h$ and a gradeability of 18%. **In section 5 a detailed list of the vehicle characteristics is reported.** It is the Fuel Cell version of the electrical vehicle *Smile* produced by FAAM Group.
In this preliminary version of our paper some details and results about the developed solutions are introduced. The architecture of the power system is introduced in the following section. Preliminary results of developed solutions are discussed in Section 3. Concluding remarks end the paper. In the final version of this paper more details about experimental results will be introduced.

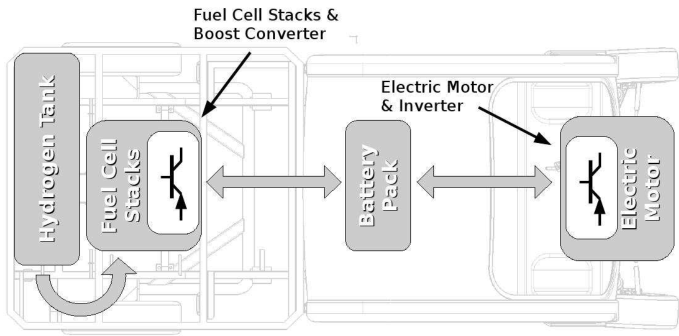

Fig. 1. *Smile* H_2 powertrain

2. FUEL CELL ELECTRIC VEHICLE

The *Smile* H_2 configuration powertrain consists of a battery pack, a fuel cell stack (PEM) and an inverter that provides power to the electric motor, as shown in Figure 1. A description about the modeling phase is provided in Cavalletti [2007]. The fuel cell stack, by a dc/dc converter (Boost), are in parallel with the battery pack and they provide the vehicle power request. The Boost converter allows to push power from the fuel cell stack to the battery. The fuel cell stack provide the mean power to the vehicle; in the other side, the battery pack supply and receive power during the acceleration or the brake conditions, respectively. At the end, the inverter converts the dc voltage into an ac voltage used to drive the motor. Along a given path, the amount of power required by the vehicle is provided by the different power devices as described by the following equation:

$$P_t(t) = P_{fc}(t) + P_{bat}(t). \tag{1}$$

where $P_t(t)$ is the power required by the inverter at each time instant, $P_{fc}(t)$ and $P_{bat}(t)$ are the power provided by the fuel cell and the battery pack, respectively. The low-level control architecture of the power devices is shown in Figure 2, where the current provided by the fuel cell stacks is controlled by the $Controller_1$, using the reference signal $I^{fc}_{ref}(T)$. The complete closed-loop system of fuel cell stacks and Boost converter is modeled by the following equations (M. Cavalletti [2008a],M. Cavalletti [2008b]) :

$$\begin{aligned}
I_{fc}(kT) &= \sum_{j=1}^{n_1} a_j^{fc} I_{fc}((k-j)T) + \sum_{j=1}^{n_2} b_j^{fc} I^{uc}_{ref}((k-j+1)T)\\
V_{fc}(kT) &= f_1(I_{fc}(kT))\\
\Delta h(kT) &= f_2(I_{fc}(kT))\\
\eta_{bs}(kT) &= f_3(I_{fc}(kT))\\
I_1(kT) &= V_{fc}(kT) I_{fc}(kT)/\eta_{bs}(kT) V_{bat}(kT)\\
I_{bs}(kT) &= \sum_{j=1}^{n_3} a_j^{bs} I_{fc}((k-j)T) + \sum_{j=1}^{n_4} b_j^{bs} I_1((k-j+1)T)
\end{aligned} \tag{2}$$

where T is the sampling time, $I_{fc}(kT)$ and $V_{fc}(kT)$ are the current and voltage provided by the fuel cell, $I^{fc}_{ref}(kT)$ is the reference signal for $Controller_1$ and represents the current required to the fuel cell stack, $I_{bs}(kT)$ is the current output of the Boost converter and $V_{bat}(kT)$ is the battery voltage at time kT. The hydrogen consumption is $\Delta h(kT)$, while $\eta(kT)$ is the efficiency curve of the Boost converter and a_j^{bs}, b_j^{bs}, a_j^{fc} and b_j^{fc} are the parameters of the dynamics of the fuel cell and of the Boost converter. The Boost steady-state current is $I_1(kT)$, the nonlinear functions f_1 is the current-voltage characteristic of the fuel cell and f_2 is the nonlinear function that relate the request of the current to the instantaneous fuel consumption of the fuel cell. The nonlinear function f_3 is the efficiency function of the Boost related to the fuel cell current $I_{fc}(kT)$. The power provided by the fuel cell is given by

$$P_{fc}(kT) = I_{bs}(kT) V_{bat}(kT). \tag{3}$$

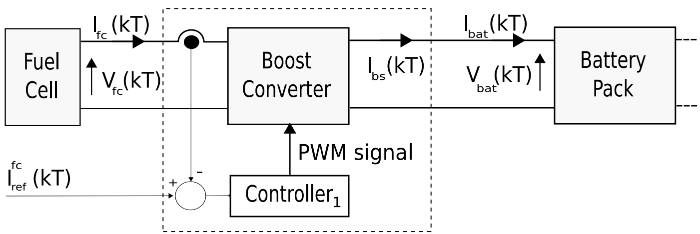

Fig. 2. Low level control architecture of the FCs current $I_{fc}(T)$ and utracapacitors current $I_{uc}(T)$ in a FCEV

In the proposed low level control architecture shown in Figure 2, the battery pack is modelled by the following equations:

$$\begin{aligned}
V_{bat}(kT) &= f_5(I_{dyn}(kT)) - R_{bat} I_{bat}(kT)\\
Q_{dyn}(kT) &= \sum_{j=1}^{n_9} a_j^{bat} Q_{dyn}((k-j)T) +\\
&+ \sum_{j=1}^{n_{10}} b_j^{bat} Q^{int}_{ref}((k-j+1)T)\\
Q_{int}(kT) &= \sum_{j=0}^{kT} I_{bat}(jT)T
\end{aligned} \tag{4}$$

where at time kT, $I_{bat}(kT)$ and $V_{bat}(kT)$ are the current and the voltage of the battery packs. $Q_{dyn}(kT)$ takes into account the dynamical aspects of the battery and $Q_{int}(kT)$ is used to model the charge of the battery. Moreover, a_j^{bat} and b_j^{bat} are the model parameters, while R_{bat} is the internal resistance of the battery pack. The power provided by the battery pack is given by

$$P_{bat}(kT) = I_{bat}(kT) V_{bat}(kT). \tag{5}$$

3. NUMERICAL RESULTS

Numerical tests of the proposed controller have been developed on *Smile* H_2 vehicle. The fuel cell stack module provides 8 Kw of maximum power, with current ranging between 0 to 160 A and the operating voltage ranging between 50 to 70 V. The mathematical model is given by (2) and the parameters are estimated using data acquired during different tests.
The Battery pack is composed of 220 lithium cells with a whole nominal voltage of $96V$ and 160 Ah. The mathematical model is given by (4). Different constraints are considered for the battery pack. The State of charge (SoC) of the battery ranges between 0 to 1. In fact, the battery may not be completely discharged or over charged. The maximum current provided by the battery is limited to 2C and the maximum regenerative current is limited to 1 C.
The total power amount $P_t(kT)$ is obtained from the request of power during a given drive test. The drive test is chosen to be representative of a typical drive condition. For this reason different road conditions (uphill, downhill, and flat), different velocities, and different drive conditions (speedup, brake) are considered. An intelligent control law is implemented to generate the Fuel Cell current reference signal $I^{fc}_{ref}(kT)$ as defined in figure 2. Three different control algorithms are investigate with the aim to design a control law to generate the $I^{fc}_{ref}(kT)$ to reduce the fuel consumption of the vehicle.

3.1 PID controller

PID controller is designed with the aim to follow the vehicle load. The controller is tuned using standard technique.

3.2 PID Fuzzy gain scheduling

The PID Fuzzy gain scheduling is a special control architecture where the control structure is similar to the single PID controller but the gain is adapted using a Fuzzy logic.

3.3 Fuzzy Controller

Fuzzy logic are used to generated the reference signal for the Fuel Cell current $I^{fc}_{ref}(kT)$ described in Figure 2. The fuzzy logic controller is based on a finite state machines in which the fuzzy logic rules are used to decide the current amount produced of fuel cell module. The logical rules are oriented to sustain the vehicle's SOC. The input variable used are two: the SOC of battery and the power request/achieved in the powertrain, whereas the output variable are the power request at the fuel cells module. In general the philosophy in back of the fuzzy rules is that: more the SOC is low and more increase the fuel cells power generated, in opposite more the SOC is high and less is the fuel cells power.

To evaluate the performance of the three proposed controller the following performance index is introduced:

$$J_{fuel} = \beta_1 \sum_{0}^{t_f} m_{\dot{f}uel}(t)dt + \beta_2|SoC_0 - SoC(t)| + \beta_3|SoC(t-1) - SoC(t)|, \quad (6)$$

where the $m_{\dot{f}uel}$ is the hydrogen mass flow, SoC_0 is the state of charge at the start of vehicle, the $SoC(t)$ is the state of charge at the t times and the $\beta_1, \beta_2, \beta_3$ are the weights used to increase the importance at state of charge sustainability. Higher penalty are connected at the strategies that use excessively the battery, because the main control objective is that the fuel cells module follower the power request.

Figures 3.3 and 3.3 shown the State of Charge of the battery pack and the evaluation of the performance index for the system using the three controllers. Table 1 summarize the performance of the three different controllers and Table 2 summarize the final performance index values. It is possible to notice that the Fuzzy controller did not provide a good performance in terms of fuel reduction and SOC. PID gain scheduling provided a better performance in terms of fuel reduction and an increase of the computation effort with the respect of a single PID controller with. The excessive use of battery pack creating an not efficiency use of the energy because several losses are introduced in the battery passing.

Table 1. Energy consumption

Controller	power source	Energy [MJ]	Total Energy [MJ]
PID	Battery Fuel Cell	0.53 3.31	3.84
PID fuzzy	Battery Fuel Cell	0.48 3.35	3.83
Fuzzy logic	Battery Fuel Cell	1.95 2.82	4.77

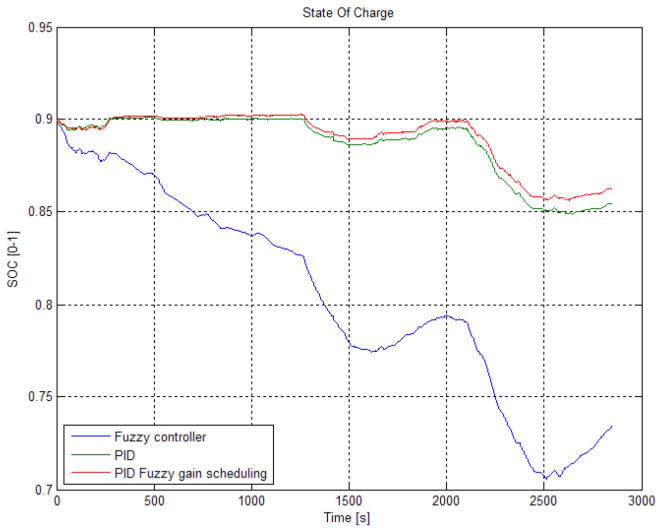

Fig. 3. State of Charge for the three proposed controllers.

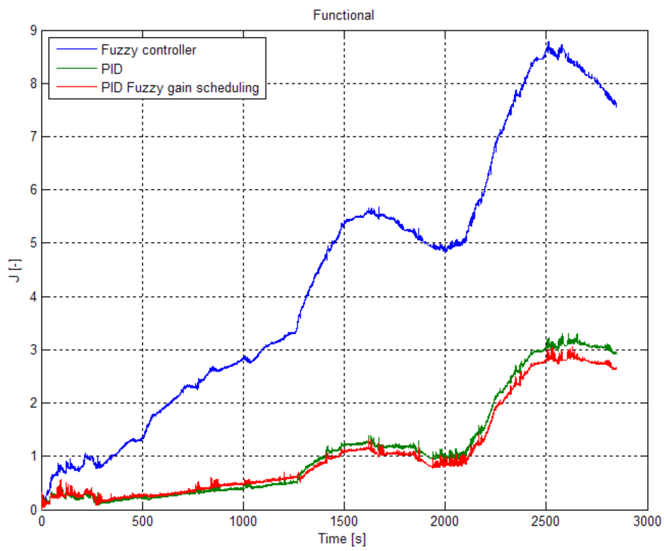

Fig. 4. The power provied by the two sources (a) and the performance index (b) using the three different control techniques.

Table 2. Performance index

Controller	Performance index	Reduction
Fuzzy logic	7.63	0%
PID	2.98	156%
Fuzzy logic	2.66	186%

4. CONCLUDING REMARKS

Fuel Cell vehicles like *Smile* H_2 can be a solution to resolve the pollution problems inside the city. In this paper a preliminary analysis of smart control techniques for the *Smile* H_2 vehicle is developed. These solutions can be used to reduce the fuel consumption during a given path. PID controller, gain scheduling and Fuzzy logic are proposed with the aim of compare the different performance of each controller. By this preliminary analysis, Fuzzy logic do not guarantee good performance in terms of fuel reduction and performance index, while PID and PID fuzzy controllers are good solutions for increasing the performance of the vehicle. Moreover, PID controller has a simple architecture and it can be easy implemented; PID fuzzy controller can increase the performance of the whole system but it requires more effort to be implemented. On the basis of this preliminary analysis the simple PID solution represents a good tradeoff between performance and implementation complexity. More results and discussions will be introduced in the final version of the paper.

5. APPENDIX A

In this section the main characteristics of the vehicle Smile H_2 are reported.

Table 3. Smile H_2 characteristics

Description	Value	Unit
Maximum load	750	kg
Maximum weight	1100	kg
Nominal Power	5	kW
Peak Power	12	kW
Hydrogen Tanks	80	Litre
Fuel Cell Stack	8	kW
Battery Pack Voltage	60	V
Battery Pack Capacity	105	Ah
Battery Pack Energy	6	kWh

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