Control strategies for fuel cell based hybrid electric vehicles: from offline to online and experimental results

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Abstract— **This paper describes two differents control strategy for a fuel cell based hybrid electric vehicle (FCHEV). The offline strategy is based on dynamic programming and the online one is based on an optimized fuzzy logic controller. Theses two strategies are then compared. Finally, the fuzzy logic controller is validated using a real FCHEV.**

I. Introduction

Proton Exchange Membrane Fuel Cells (PEMFC) appear to be suitable for vehicular applications [1]–[3] due to their low operating temperature range (60-90 °C) [4] and their high power density. A Hybrid Electric Vehicule (HEV) based on PEMFC and batteries leads to zero emission and enables kinetic energy recovery during braking phases [5], [6]. The control strategy of these two sources is directly linked to hydrogen consumption [7]. Two kinds of control are found in the litterature: on the one hand, offline controls aim at optimizing the power split between the two sources for a known driving cycle; on the other hand, online controls are based on real time controller such as fuzzy logic [8]–[10], neural network [11] or predictive control [12], [13]. This paper compares theses strategies on differents scenarios of driving cycles [14], [15]. The comparison will permit to the online controller to be adapted based on the driving cycle using, for example, learning algorithms. In a first part, the model of a fuel cell based hybrid electric vehicle (FCHEV) is described. Then, an offline control based on a dynamic programming (DP) algorithm is used to obtain the best fuel economy for a known driving cycle. A fuzzy logic controller is then defined for the same driving cycle and both strategy are compared. Then, a genetic algorithm is used to improve the online strategy in order to approach as best as possible the offline control strategies results. Finally, the last section presents the experimental validation of the online control on a fuel cell hybrid vehicle with fuzzy logic implementation will be presented in order to validate the simulated results. The experimental results show that the optimized controler is really close to optimal results obtained with DP.

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II. VEHICLE'S CHARACTERISTICS

A. Vehicle model

The vehicule considered for this study is a series hybrid electric vehicule based on a PEM fuel cell and batteries as shown in Figure 1 .

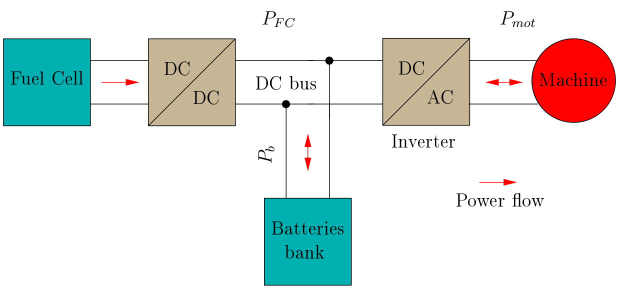

Fig. 1. Vehicle's architecture

The PEMFC is connected to the DC bus via a DC-DC converter whereas the batteries are directly linked to the bus. Only one degree of freedom for the control strategy is possible: only the fuel cell current i_{FC} can be controlled. The vehicle power as a function of the speed is given by (1) [16]:

$$P_v(t) = v\left(m_v(t)\frac{\mathrm{d}}{\mathrm{d}t}v(t) + F_a(t) + F_r(t) + F_g(t) + F_d(t)\right) \tag{1}$$

where F_a is the drag force, F_r the rolling friction, F_g the force caused by gravity when driving on non-horizontal roads and F_d the disturbance force that summarizes all other effects. The power split between the fuel cell P_{FC} and the batteries P_b is given by (2).

$$P_v(t) = \eta_{FC}\, P_{FC}(t) + \eta_b\, P_b(t) \tag{2}$$

where η_{FC} is the fuel cell efficiency and η_b is the battery efficiency.

Due to the architecture, only the fuel cell can be actively controlled.

B. Fuel cell model

The PEMFC is used as the primary source of energy and the objective of the strategy is to minimize the hydrogen consumption given by (3) [17], [18] :

$$m_{H2} = \int_0^t \frac{M_{H_2}\, n_c}{2\, F} I_{FC}(t)\, \mathrm{d}t \tag{3}$$

where m_{H_2} is the hydrogen mass, M_{H_2} is the hydrogen molar mass, n_c is the number of cells, I_{FC} the fuel cell current and F the faraday constant $(96, 487\,\mathrm{C})$. The fuel cell current I_{FC} is calculated based on the polarization curve given by Figure 2.

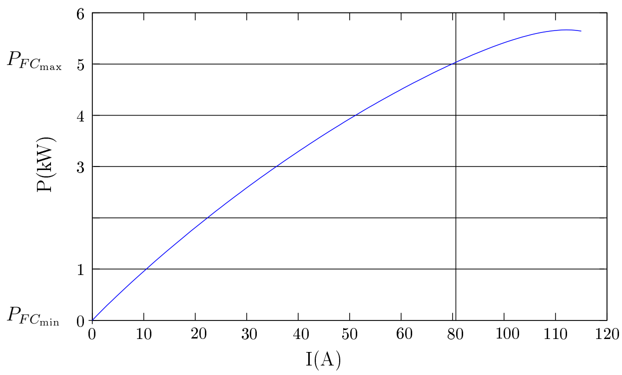

Fig. 2. Fuel cell power

III. OFFLINE CONTROL STRATEGY

The offline control strategy objective is to find the minimum hydrogen consumption for a known driving cycle [19], [20]. The consumption minimization problem can be written as a problem of optimal control for discrete system [12].

A. Problem formulation

The battery's state of charge (SoC) $x(k)$ can be considered as a dynamic system. The system can be written as:

$$x(k+1) = x(k) + P_b\, \eta_b\, T_s \tag{4}$$

$$\eta_b = \begin{cases} 0.95 & \text{if } P_b(t) < 0 \\ 1 & \text{if } P_b(t) \geq 0 \end{cases} \tag{5}$$

where P_b is the battery power level defined by (2), η_b the battery efficiency (0.95 for charge and 1 for discharge) and T_s the sampling time. The chosen criterion for N samples can be written as:

$$J = \sum_{k=0}^{N-1} \Delta m_{H2}(P_{FC}, k)\, T_s \tag{6}$$

where $m_{H2}(P_{FC}, k)$ is the hydrogen mass consummed for the power P_{FC} between two sampling times. According to fig 2, the fuel cell power is obviously limited:

$$\mu_{FC} = P_{FC_{\text{min}}} < P_{FC} < P_{FC_{\text{max}}} \tag{7}$$

where $P_{FC_{\text{min}}}$ = 0 kW and $P_{FC_{\text{max}}}$ = 5 kW.

Morever, the FCHEV studied here is not plugin, so the remaining state of charge at the end of the cycle needs to be the same as the one at the begining [21], and the state of charge's boundaries on x must be limited by the batteries charge, and discharge efficiencies. The discrete-time optimal problem can be then formuled as following:

$$\min_{P_{FC} \in \mu_{FC}} \quad \sum_{k=0}^{N-1} \Delta m_{H2}(P_{FC}, k)\, T_s \tag{8}$$

$$x(k+1) = x(k) + P_b\, \eta_b\, T_s \tag{9}$$

$$x_0 = SoC_{init} \tag{10}$$

$$x_N = SoC_{final} = SoC_{init} \tag{11}$$

$$x_k \in [0.4\,, 0.9] \tag{12}$$

$$N = \frac{T_{dc}}{T_s} \tag{13}$$

B. Dynamic programming algorithm

To solve this optimisation problem, a dynamic programming algorithm is used. This algorithm has been proposed by Sundstorm and Guzzella in [22]. The control input variable P_{FC} is discretized by step of 100 W such that $P_{FC} = [0\,, 100\,, 200 ... 4900\,, 5000]$ and the algorithm calculates the minimum cost-to-go function $C = \min(m_{\text{h}_2})$ at every node in the discretized state-time space with the constraint $x(k)$ given by (8) and the feasible inputs solutions give by (7).

IV. Online control strategy

A. Real time control strategy definition

The previous offline control strategy is only relevant for a known driving cycle. The online control strategy focuses on real time strategy without predictive informations. This strategy aims at reducing the hydrogen consumption and maintain the final state of charge in an optimal zone chosen by the controller. In the offline control strategy, the input control variable P_{FC} can be chosen between 0 W and 5,000 W with a step of 100 W. Due to the lack of predictive information in real time strategy, the controller will focus on four working modes (states) forced by the battery's state of charge (SoC):

- *Low SoC*: the fuel cell needs to operate upper to its optimal running point;
- *Optimal SoC*: the fuel cell can run within its optimal power zone, the batteries absorb or provide the peaks of power;
- *High SoC*: the fuel cell can work around its optimal running zone;
- *Very high SoC*: the fuel cell is switched off and the vehicle runs in pure electric mode.

B. Fuzzy logic controller

To implement the following states, a fuzzy logic controller develloped by Blunier *and al.* is used [23]. Fig 3 gives the membership functions of the controller for different fuel cell power levels.

Figure 4 shows the simulation results of the fuzzy logic controller for the LA92 driving cycle. The state of charge varies in its optimal state of charge window. The fuel cell current is sometimes reduced when the state of charge is too

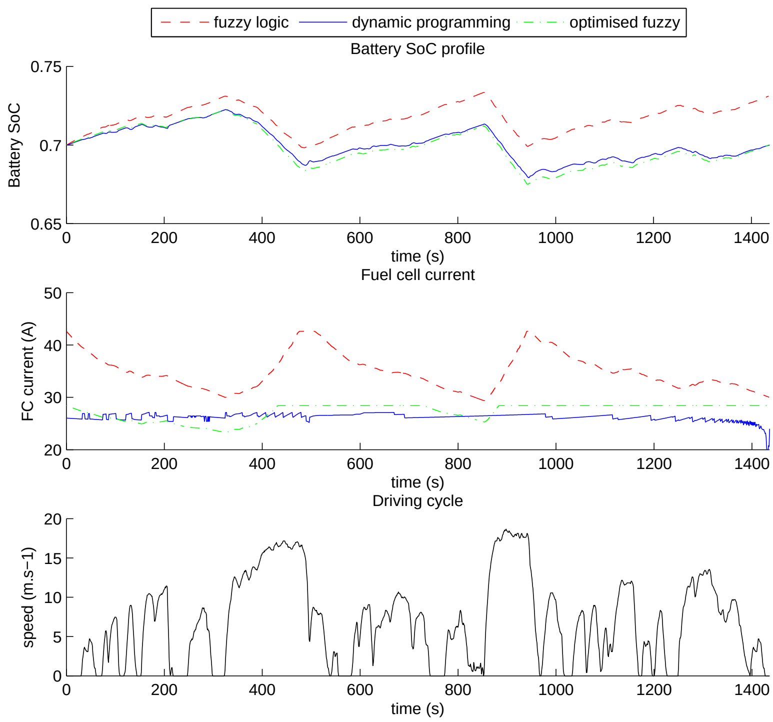

Fig. 4. Simulation results

TABLE I
HYDROGEN CONSUMPTION FOR SEVERAL ARCHITECTURES AND CONTROLS

	Fuel cell power (kW)	**Battery capacity (Ah)**	**H_2 consumption (g)**
Stand alone fuel cell vehicule	13	0	102
Fuzzy logic controller	5	65	63
Optimised Fuzzy logic controller	5	65	49
Dynamic programming	5	65	40

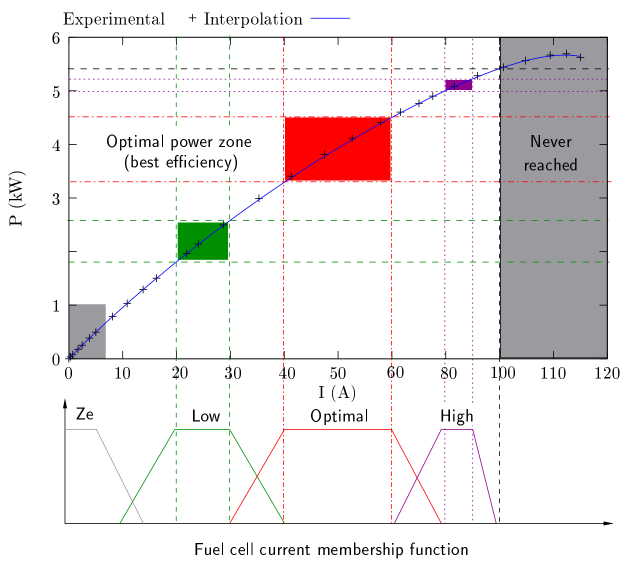

Fig. 3. Fuel cell fuzzy logic controller

high. Table I shows the hydrogen consumption for the driving cycle using the non optimized controller.

V. Strategy Comparison

According to fig 4, the dynamic programming strategy allows to find the optimum fuel economy while keeping the final state of charge at its initial value. Knowing the driving cycle allows the strategy to keep a constant fuel cell current value minimizing the hydrogen consumption and charging the battery during stop phases of the driving cycle. However, the online strategy cannot predict the power needed during the cycle and keep the state of charge in its optimal zone, decreasing the fuel cell when the state of charge is to high. Table I shows the hydrogen consumption for both strategies and for a stand alone fuel cell vehicle without batteries. Hybridization and control strategy permit to improve the fuel cell economy up to 40 % for a fuzzy controller and up to 60 % for dynamic programming. The offline strategy can be used as a reference to compare others controls strategies to the optimal power split profile for a selected driving cycle. The fuzzy logic controller used here is not optimal: the final state of charge is higher than the initial, and the hydrogen consumption is also higher than the DP results. However, this strategy allow to run others driving cycles by the vehicle with the same results [24] (SoC remaining in the optimal zone) compare to the offline strategy which have to run the DP algorithm to find the optimal power split profile, which is not able to be done on real time. Consequently, the offline strategy cannot be applied in vehicle if the driving cycle is not known or predicted [25]. In the next section, the membership functions of the online fuzzy logic controller will be tuned in order to improve the online controller and approach DP results.

VI. Fuzzy logic controller's optimisation using genetic algorithm

A. Problem formulation

The previously described fuzzy logic controller focused on maintaining the state of charge of the battery in the optimal zone (around 0.7) in order to respect the constraint given by (11). In order to reduce the hydrogen consumption, the memberships functions defining the fuel cell current (as described in Figure 3), are tuned. Fig 5 gives an example of the configuration of the four membership function. Each functions are trapezoidal and four variables $x\,(i\,,j)$ can be associated where i is the number of the function (1 for Ze, 2 for Low, 3 for Optimal and 4 for High) and j is the number of the variable, as described in the figure ($j \in [1\,,4]$).

The optimisation aims at reducing the hydrogen consumption by varying theses parameters while respecting the following constraint:

$$x\,(i\,,(j-1)) \leq x\,(i\,,j) \tag{14}$$

$$x\,((i-1)\,,3) < x\,(i\,,2) \tag{15}$$

$$x\,(i\,,j) \in [0\,,130] \tag{16}$$

$$SoC_{final} = SoC_{init} \tag{17}$$

B. Genetic algorithm

To solve this optimisation problem, a genetic algorithm is used. A candidate solution is composed of the sixteen variables $x\,(i\,,j)$ defined previously and the population is set to a hundred of candidate solutions. The population is randomly initialised, respecting the constraint given by (14) and the number of iterations is set to ten thousands. The fitness function run the fuzzy logic controller tuned by each candidate solution on the LA92 driving cycle and return the hydrogen consumption and the SoC_{final}. Figure 4 and Table I show the result of the optimised fuzzy logic controller by the best candidate solution. The hydrogen can be reduced by 22 % from the standard fuzzy controller. heas shown on Fig 4 fuel cell current and SoC profile are close to the dynamic programming ones, which are the optimum for this driving cycle.

VII. Experimental validation on a real fuel cell hybrid electric vehicle

The designed fuzzy logic controller presented in section IV-B is implemented in a FCHEV which has the following caracteristics:

- *Vehicle mass*: 578 kg;
- *Front surface*: 2 m²;
- *Drag coefficient*: 0.7;
- *Rolling coefficient*: 0.015;
- *Battery technology*: Lead acid;
- *Battery capacity*: 40 Ah;
- *Battery cells number*: 6;

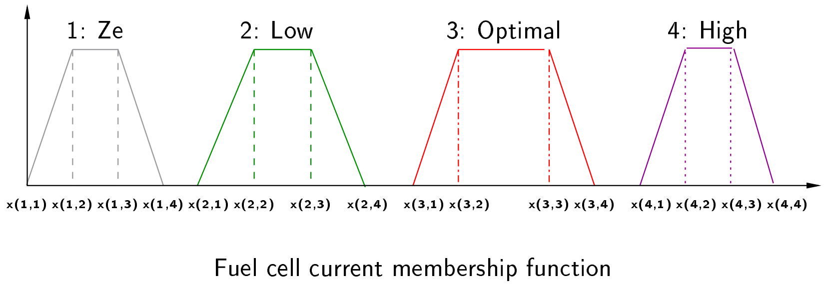

Fig. 5. Fuzzy membership's variables

- *DC-bus voltage*: 72 V;
- *Fuel cell power*: 2 kW.

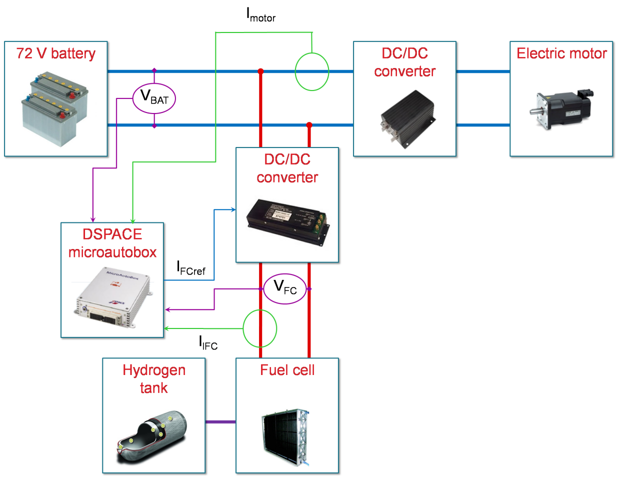

Fig. 6. Vehicle architecture

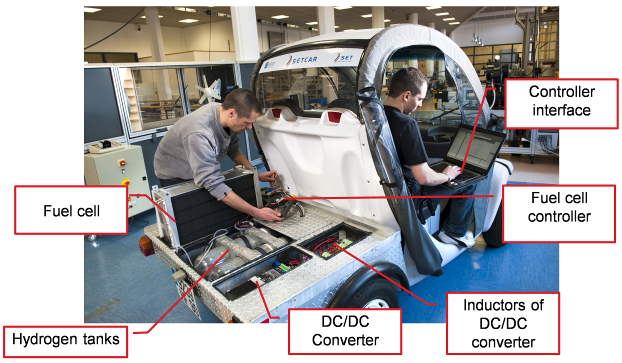

Fig. 7. Fuel cell hybrid electric vehicle

Fig 7 shows a picture of the vehicle and fig 6 shows the architecture of the vehicle. The fuel cell current is controlled using a buck DC-DC buck converter [26], [27] from 120 V to 72 V. The batteries are directly linked to the DC-bus. Current and voltage sensors give informations to the DSPACE Microautobox controller where fuzzy logic is implemented, and the analog output controls the DC/DC converter. The power needed by the motor is emulated by an active load running the LA92 driving cycle with vehicle parameters.

Since lead acid batteries does not have battery management system [28], the state of charge needs to be evaluated using the current and voltage given by sensors.

A. Experimental state of charge determination

The state of charge of the batteries is given by (18) :

$$SoC(t) = \frac{C_{battery}}{\int_{x_0}^{t} i_{motor}(t) - i_{FC}(t)\ dt} \tag{18}$$

Where $SoC(t)$ is the state of charge at each time t, $C_{battery}$ is the battery capacity in Ah, i_{moto} and i_{FC} are the current needed by the motor (active load) and given by the fuel cell and x_0 is the initial battery capacity.

To determine the initial battery capacity, a charge/discharge experimentation is run in order to determine the relation between the SoC and the open circuit voltage (OCV). Fig 8 shows the results of this experimentation for a discharge at 50 Ah from 100 % to 0 %

When the vehicle start, OCV is given by the voltmeter and the initial state of charge is calculated. The state of charge is then computed at each time step t of the fuzzy controller.

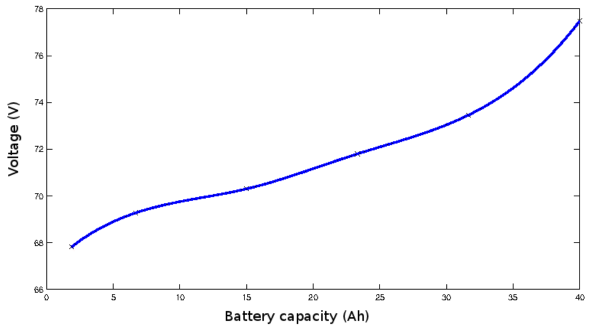

Fig. 8. Remaining battery capacity as a function of OCV

B. Fuzzy controller implementation

The fuzzy controller is implemented in a DSPACE microautobox which is runs at 10kHz. As describe in fig 6, the fuzzy controller controls the DC-DC converter through analog output from 0 V to 10 V corresponding to a fuel cell current range between 0 A and 30 A. the fuzzy zone is defined as:

- *Low SoC*: Below 50 % SoC, fuel cell is running at maximum power (2 kW);
- *Optimal SoC*: from 60 % to 70 % SoC, fuel cell is running at optimal point (1,4 kW);
- *High SoC*: from 70 % to 60 % SoC, fuel cell is low (0.7 kW);
- *Very high SoC*: up to 80 % SoC, fuel cell is switched off.

Fig 9 shows the results for LA92 driving cycle emulated by the active load for the experimentation and the results for the simulation with the same fuzzy logic parameters. The initial state of charge is 80 %. In a first part, the fuel cell is switched off in order to decrease the SoC in its optimal zone. The state of charge is then in the High zone, the fuel cell running point (20 A) is under the optimal working point (where the efficiency is the best) and the SoC keep decreasing steadily to reach the optimal zone. Finally the fuzzy logic controller maintains the state of charge in this zone (between 60 % and 70 %). The simulation results fit with the experimentation: the fuel cell current is almost the same during all the cycle, but the state of charge shows some small differences: in fact, the experimental state of charge determination amplify the measurement errors. However, this error is acceptable. The hydrogen consumption is 31 g for experimentation and 25 g for simulation. Experimentation consumption is higher because the fuel cell model does not take into account the hydrogen purges of the fuel cell.

VIII. CONCLUSION

Both offline and online control strategy allow to improve the fuel economy of a fuel cell hybrid vehicule. Such a controler can also be applied to an internal combustion engine based hybrid vehicles. Each strategy must be used in particular case: the offline can predict the control knowing, a priori, the driving cycle whereas the online control strategy is adapted for real time energy management. Optimising the online controller and comparing it to the offline results, which are the optimum, allows to tune the online controller for a particular driving cycle. Future works will aim at applying this methodology for several patterns of driving cycles to create a macro controller which can recognize, based on a neural-network based learning algorithm, the type of cycle (urban, high-way...) and adapts the fuzzy logic controller with the best parameters in real time.

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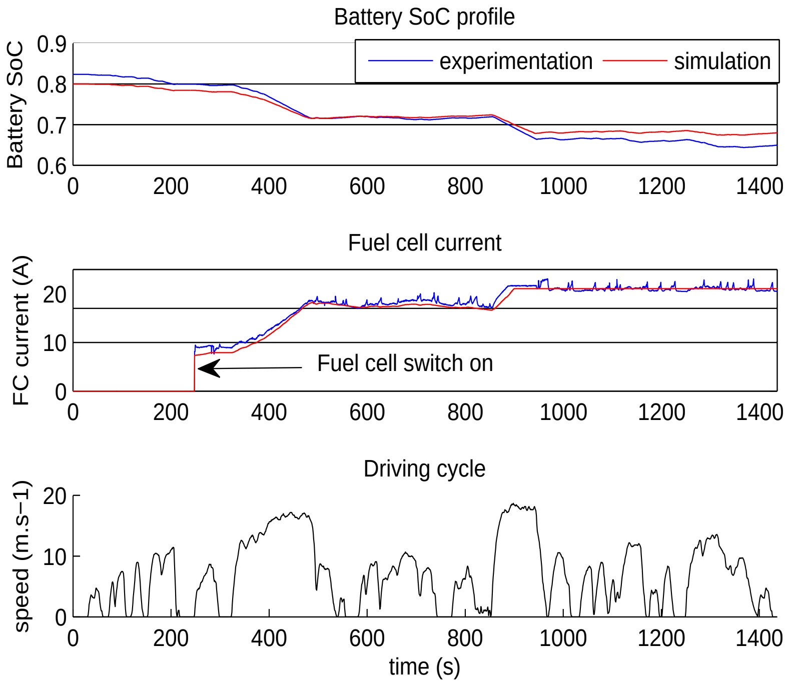

Fig. 9. Experimental results for fuzzy logic controller with LA92 driving cycle

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