

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

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Abstract— This paper describes two different control strategies for a fuel cell based hybrid electric vehicle. The offline strategy is based on dynamic programming and the online one is based on a fuzzy logic controller. These two strategies are then compared and the online results are improved with a genetic algorithm optimisation.

I. INTRODUCTION

Proton Exchange Membrane Fuel Cells (PEMFC) appear to be suitable for vehicular applications [1] due to their low operating temperature range (60-90 °C) [2] and their high power density. A Hybrid Electric Vehicle (HEV) based on PEMFC and battery leads to zero emission and enables kinetic energy recovery during braking phases. The control of the two sources of energy on this vehicle is directly linked to hydrogen consumption [3]. Two kinds of control are found in the literature: on the one hand, the offline control aims at optimizing the power split between the two sources for a known driving cycle; on the other hand, the online control is based on real time controller such as fuzzy logic [4], neural network [5] or predictive control [6]. This paper compares these strategies on different scenarios of driving cycles. The comparison will permit 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 is described. Then, an offline control based on a dynamic programming 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 strategies are compared. Finally, a genetic algorithm is used to improve the online strategy in order to fill the gap between the two results of online and offline control strategies.

II. VEHICLE'S CHARACTERISTICS

A. Vehicle model

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

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) [7]:

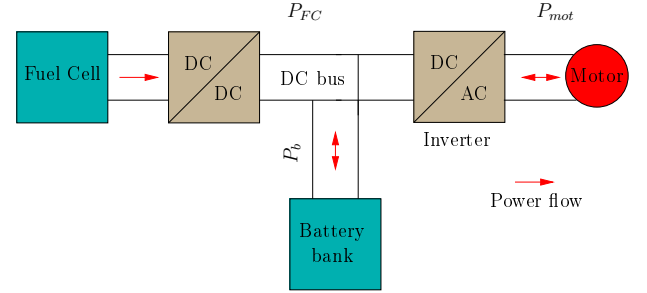


Fig. 1. Vehicle's architecture

$$P_{mot}(t) = v \left(m_v(t) \frac{d}{dt} v(t) + F_a(t) + F_r(t) + F_g(t) + F_d(t) \right) \quad (1)$$

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).

$$P_{mot}(t) = \eta_{FC} P_{FC}(t) + \eta_b P_b(t) \quad (2)$$

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) [8], [9]:

$$m_{H_2} = \int_0^t \frac{M_{H_2} n_c}{2 F} I_{FC}(t) dt \quad (3)$$

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 C). The fuel cell current I_{FC} is calculated based on the polarization curve given by Figure 2.

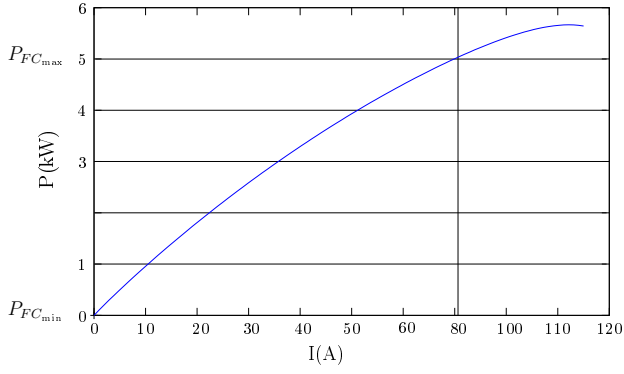


Fig. 2. Fuel cell power

III. OFFLINE CONTROL STRATEGY

The offline control strategy objective is to find the minimum hydrogen consumption on a known driving cycle [10], [11]. The consumption minimization problem can be written as a problem of optimal control for discrete system [6].

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:

$$x(k+1) = x(k) + P_b \eta_b T_s \quad (4)$$

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

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

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

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

$$\mu_{FC} = P_{FC_{min}} < P_{FC} < P_{FC_{max}} \quad (7)$$

where $P_{FC_{min}} = 0$ kW and $P_{FC_{max}} = 5$ kW. Moreover, the hybrid electric vehicle 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 beginning [12], and the state of charge's boundaries on P_b must be limited by the batteries charge, and discharge efficiencies. The discrete-time optimal

problem can be formulated as following:

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

$$x(k+1) = x(k) + P_b \eta_b T_s \quad (9)$$

$$x_0 = SoC_{init} \quad (10)$$

$$x_N = SoC_{final} = SoC_{init} \quad (11)$$

$$x_k \in [0.4, 0.9] \quad (12)$$

$$N = \frac{T_{dc}}{T_s} \quad (13)$$

B. Dynamic programming algorithm

To solve this optimisation problem, a dynamic programming algorithm is used. This algorithm has been given by Sundstorm and Guzzella in [13]. The control input variable P_{FC} is discretized by step of 100 W such that $P_{FC} = [0, 100, 200 \dots 4900, 5000]$ and the algorithm calculates the minimum cost to go function $C = \min(m_{h2})$ 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 suited for a knowing 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:

- *Low state of charge*: the state of charge of the batteries is low, the fuel cell needs to operate upper to its optimal running point;
- *Optimal power zone*: the fuel cell run within its optimal power zone, the batteries absorbs the peaks of power;
- *Charge sustaining*: the batteries state of charge is high, the fuel cell can work around its optimal running zone;
- *Electric Zone*: the batteries state of charge is very high, the fuel cell is switched off and the vehicle runs in electric mode.

B. Fuzzy logic controller

To implement the following states, a fuzzy logic controller developed by Blunier and al. is used [14]. Figure 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

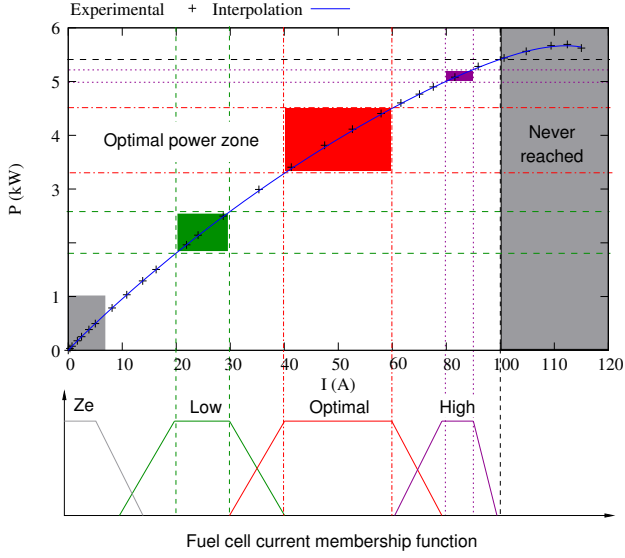


Fig. 3. Fuel cell fuzzy logic controller

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

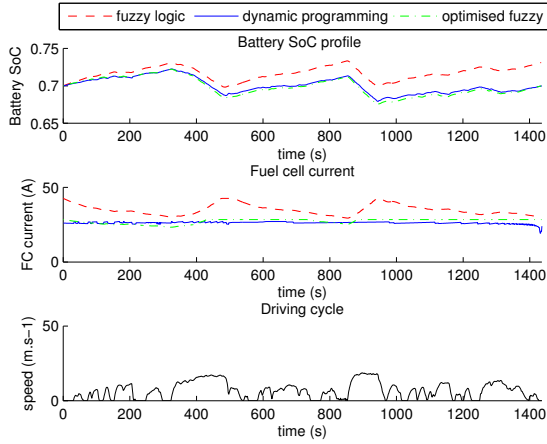


Fig. 4. simulation results

V. STRATEGY COMPARISON

According to Figure 4, the dynamic programming strategy allows to find the optimum fuel economy while keeping the final state of charge as 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. Therefore, 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. 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. In the next section, the membership functions of the online fuzzy logic controller will be tuned in order to reduce the gap between the offline and online results.

VI. FUZZY LOGIC CONTROLLER'S OPTIMISATION USING GENETIC ALGORITHM

A. Problem formulation

The previously described fuzzy logic controller focus on maintaining the state of charge of the battery pack in the optimal zone (around 0.7) in order to respect the constraint given by (17). In order to reduce the hydrogen consumption, the memberships functions defining the fuel cell current (as described in Figure 3), are tuned. Figure 5 represents an example of the configuration of the four membership function. Each functions are paralleloids 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 ($j \in [1, 4]$).

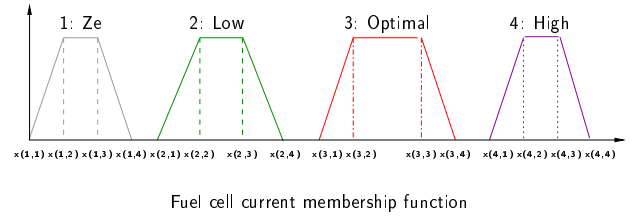


Fig. 5. Fuzzy membership's variables

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

$$x(i, (j-1)) \leq x(i, j) \quad (14)$$

$$x((i-1), 3) < x(i, 2) \quad (15)$$

$$x(i, j) \in [0, 130] \quad (16)$$

$$SoC_{final} = SoC_{init} \quad (17)$$

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. The fuel cell current and SoC profile are close to the dynamic programming ones, which are the optimum for this driving cycle.

TABLE I
HYDROGEN CONSUMPTION FOR SEVERAL ARCHITECTURES AND CONTROLS

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

VII. CONCLUSION

Both offline and online control strategy allow to improve the fuel economy of a fuel cell hybrid vehicle. Such a controller can also be applied to a ICE-based hybrid vehicle. 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 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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