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IEEE VTS Motor Vehicle Challenge 2017
Fuel Cell/Battery Vehicle Energy Management – Key Issues

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In October 2016, an international challenge devoted to the energy management of a fuel cell/battery vehicle was launched during the 2016 IEEE Vehicle Power and Propulsion Conference (VPPC), in Hangzhou, China. The vehicle driving cost, which includes the hydrogen and the source degradation costs, was used as a base of comparison. Following the success of this first initiative, this paper analyses the best participant energy managements. It appeared that well designed Energy Management Strategies (EMS) lead to reduce significantly the trip cost while ill-designed EMS may lead to high fuel consumption or premature source degradations. Tight deadlines have deliberately limited the development times, but the best results are close to the theoretical dynamic programming optimum. Knowing in advance the mission profile also does not appears so important because the best developed strategies have quite similar results than for the dynamic programing optimal strategy.

A complex system

The increase in the average temperature of the planet has been observed since the industrial era. Transport contributes significantly to climate change. The greenhouse gases created by the burning of fossil fuels activate this phenomenon. In *50* years, the number of cars could increase by *160* % [1], [2]. The International Energy Agency (IEA) thus calls for a *60* % reduction in transport emissions in *2050* compared to *1990* to limit the rise in temperature to *2* °C compared to the pre-industrial era. Cleaner means of transport must be offered.

Electric, hybrid and Fuel Cell vehicles are developing to face this challenge [2]. Electric vehicles have a limited range and long charging time. Hybrid vehicles yet require fossil fuel. Fuel cell vehicles are based on hydrogen as energy source. As hydrogen can be produced by the electrolysis of water, this energy could be “clean” and sustainable. However, the electric production has also to be considered.

Today, FC vehicles appear in the automotive market (e.g. Toyota, Honda and Hyundai) due to some advantages. For an equivalent energy storage mass, the autonomy of a fuel cell vehicle (FCV) is higher than a battery electric vehicle (BEV) one. With a full tank of H_2, a driver can expect to travel about *500* km (*310* mi), against *200* km (*130* mi) for an electric car and *1,000* km (*620* mi) for a conventional thermal vehicle. However, even if the energy density of hydrogen is high (*33.3* kWh/kg), the current hydrogen storage capacities are limited (generally *5.5* kg of H_2 pressurized at *700* bar) [3]. Moreover, the hydrogen tank fills up in a few minutes in station whereas a full charge of a battery electric vehicle lasts several hours. However, FCVs have to face some issues.

The FC converts the chemical hydrogen energy into electrical energy to supply an electric traction motor. However, fast power transients can lead to a gas starvation, which will permanently damage the FC [4]. The traction of a vehicle requires high power dynamics, which is harmful to the FC. Furthermore, the energy flow of FC systems is unidirectional, which does not allow recovering braking energy [5]. Batteries can then be used as a secondary source to handle the power transients and to recover braking energy. This secondary source allows extending the FC lifetime and reduces its related cost. In this way, Toyota uses a *1.6* kWh nickel-metal hydride (NiMh) battery to assist the *114* kW FC in its Mirai car [6]. Similarly, lithium batteries supply the Honda FCX Clarity or the Hyundai Tucson FCEV [7], [8].

The FC/battery vehicle represents a complex system. Its control can be organized in two parts: the local control and the Energy Management Strategy (EMS) (figure 1). The local control aims to tune the variables of each subsystem (light blue blocks in figure 1). The EMS aims to distribute the energy between the subsystems from the driver requests (dark blue block in figure 1). The EMS leads to the references of the local control. The vehicle performances are then dependent on the target objectives, e.g. the reduction of the fuel consumption. Thus, the EMS appears as a key element in the operation of a FC/battery vehicle. The EMS determines the distribution of the energy flows between the energy sources according to a vehicle mission profile and the technical specifications of the sources (green oval pictograms in figure 1).

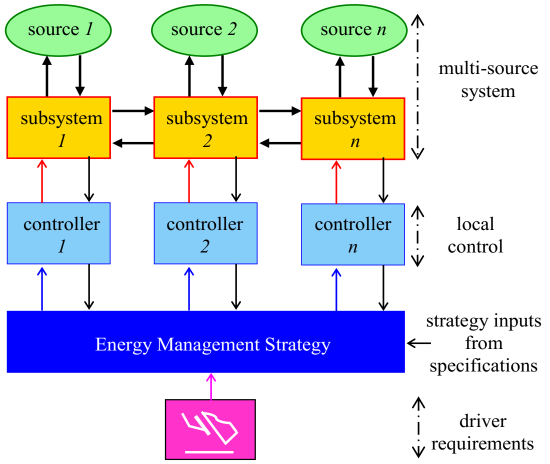


Figure 1 *Multi-source system management*

Motivation

Over the last 10 years, several works have been devoted to the energy management of FC/battery vehicles. For example, over the period from January *1*, *2007* to May *1*, *2017*, IEEE Xplore identifies *54* journals and magazines, and *309* conference papers on this subject (keywords: battery, fuel cell, management, vehicle). Minimization of fuel consumption, maximal efficiency or maximal power identification, degradation or cost minimization are used as criteria to build EMS. For multi-source vehicles, EMS can be distinguished: heuristic and optimal strategies [9]. Heuristic strategies rely on rules based on human expertise and depending on strategy inputs. Optimization-based strategies mathematically defined specifications in a cost function to reach an optimal behavior for a specific driving cycle. However, optimization-based strategies cannot be used in real time because they need long computation time and the considering driving cycle must be known in advance.

Based on fuel consumption or source degradations arguments, different works propose *ad hoc* strategies for energy management of FC/battery vehicles. However, it is difficult to compare the performance and effectiveness of these EMSs without a common subject and criteria. In this way, an international challenge was recently created to compare different strategies for a FC/battery vehicle [10]. Within the framework of this challenge, a complete vehicle model and the associated local control were provided. The participants had to design the EMS. However, in order to consider a realistic driving application, the knowledge of the scoring driving cycle was not known beforehand and off-line optimal strategies were forbidden. The developed EMS should be designed to minimize two important aspects identified in the literature: the fuel consumption and the energy source degradations. An equivalent global cost function $\$_{global}$ (in US$) was defined to combine the consumption and the degradation criteria. The global trip cost $\$_{global}$ then serves as a common criterion to compared the developed participants EMSs. The aim of this challenge was then to develop a robust on-line EMS to:

1 ***Increase the FC lifetime*** which depends on the FC power operation and start/stop events. During a trip, the cost of the FC system degradation $\$_{\Delta fc}$ is calculated depending on a degradation function Δ_{fc} and the FC system cost. The complete model of the degradation and cost functions are detailed in [10].

2 ***Minimize the hydrogen consumption*** which is a function of the FC current. Considering the H_2 price, the trip cost $\$_{H2}$ is calculated considering the total fuel consumption.

3 ***Limit the battery State of Charge (SoC).*** The battery degradation Δ_{bat} depends on its SoC and on the power transients. For example, high currents in the battery reduce its lifetime. The battery system degradation cost $\$_{\Delta bat}$ is then calculated from Δ_{bat} and the initial battery cost.

Depending on the battery *SoC* at the end of the driving cycle, a battery charge penalty is finally set up. In this way, the battery is full charged at the best FC efficiency point at the end of a driving cycle. This consider the related additional H_2 consumption and the FC and the battery degradations. The cost of this recharge $\$_{charge}$ is then taken into account for the global cost function definition $\$_{global}$:

$$\$_{global} = \$_{\Delta fc} + \$_{H2} + \$_{\Delta bat} + \$_{\text{charge}} \quad (1)$$

Realization

The studied vehicle traction is based on the commercial Tazzari Zero battery Electric Vehicle (EV) [11] (figure 2). The studied FC/battery vehicle is composed of a 15 kW induction machine fed by a voltage-source-inverter through the ESS, composed of a Lithium Iron Phosphate (LiFePO4) battery pack, a Proton Exchange Membrane Fuel Cell (PEMFC) and its corresponding smoothing inductor and chopper (figure 3). This configuration limits the number of converters and therefore the weight, the volume and the cost of the vehicle because the battery is directly connected to the traction subsystem. The vehicle is limited to a maximal speed up of *85* km/h (*53* mph). The main vehicle parameters are presented in table 1.

Figure 2 *Tazzari Zero*

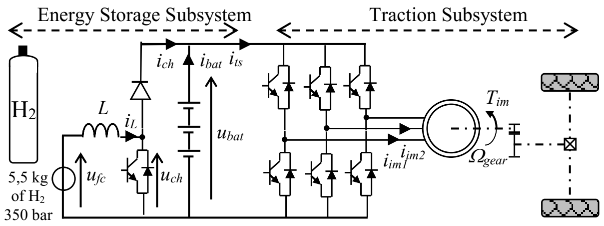


Figure 3 *Studied FC/battery vehicle architecture*

Fuel Cell	*40-60* V, *16* kW
Smoothing inductors	*5.5* mΩ, *0.25* mH
Battery	*80* V, *40* Ah
Electric drive	*15* kW
Vehicle empty weight	*698* kg

Table 1 *Fuel cell/battery vehicle parameters*

The complete vehicle model organization and control is depicted thanks to the Energetic Macroscopic Representation (EMR) in [10]. EMR is a graphical description for the definition of control schemes of complex energetic systems [12], [13]. This clearly differentiates the system model, the local control and the management strategy. A simplified descriptive diagram of the considered FC/battery vehicle management is depicted in figure 4.

Depending on the driver requirements, the traction subsystem imposes a traction current to the ESS, which provides the battery voltage. From inputs to be defined, two strategy-level outputs needed to be managed by the participants (Energy source and braking strategies block in figure 4). First, the mechanical and electrical distribution of the braking force F_b must be realized from a braking distribution parameter k_D. Secondly, the FC current reference value $i_{fc\text{-}ref}$ must be determined to supply the battery. This current is controlled through the chopper modulation ratio tuning input m_{ch}.

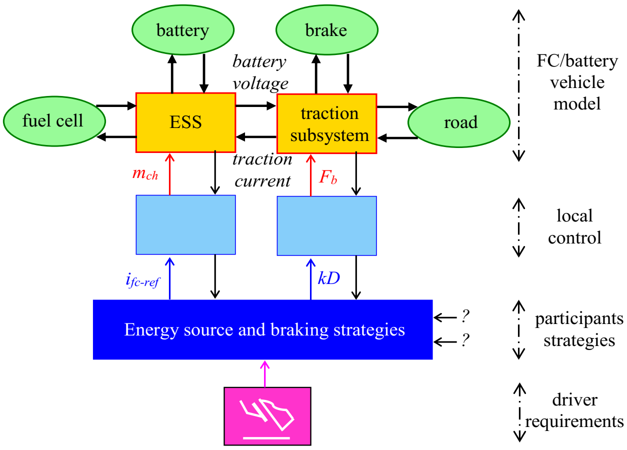
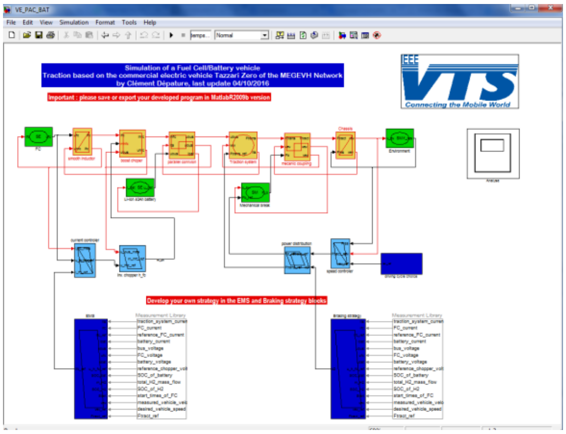


Figure 4 *Considered FC/battery vehicle management*



Simulation of a Fuel Cell/Battery vehicle
Traction based on the commercial electric vehicle Tazzari Zero of the MEGEVH Network
by Clément Dépature, last update 04/10/2016

Important : please save or export your developed program in MatlabR2009b version

Develop your own strategy in the EMS and Braking strategy blocks

Figure 5 *Downloadable Matlab Simulink^{TM} simulation program*

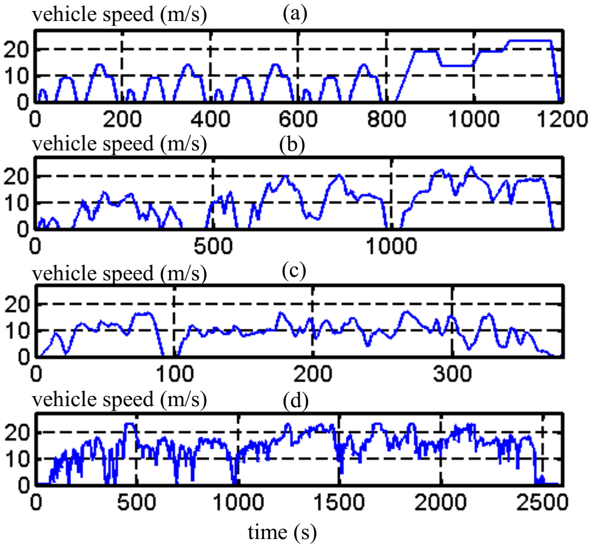


Figure 6 *Considered driving cycles: (a) Adapted NEDC, (b) WLTC, (c) urban driving cycle and (d) scoring driving cycle*

In order to develop and to test their strategies, a unique simulation program capable of simulating different strategies with the same local control was developed and provided to the participants. This was built under the Matlab Simulink^{TM} software (figure 5). Then, the EMR and the control scheme of the vehicle have been implemented in Matlab Simulink^{TM} using an EMR Simulink^{TM} library with basic elements. This program is totally open and still downloadable [14]. It can be used according to a user interface in order to build an expertise and facilitate the EMS developments (choice of the simulated driving cycle (figure 6a,b,c), end of simulation graphs and report, etc.). A dedicated website [14], a technical email, a forum assistance and the related VPPC *2016* paper [10] have helped the participants in their achievements. The strategy scoring was carried out on a driving cycle unknown to the participants (figure 6d). This *32.6* km driving cycle include urban and extra urban parts and was obtained from a real

Tazzari Zero driving test. Finally, an optimal Dynamic Programming (DP) strategy has been developed for the scoring step. This has been carried with the knowledge of the driving cycle to determine if the participant's strategies are close to the theoretical global optimal cost.

Participation

In total, *48* academic (*54 %*), student (*40 %*) and professional (*6 %*) participants from *14* different countries took part in the challenge (figure 7). The teams that developed the best EMSs received an award that consisted of: a certificate, an invitation to write and present a paper for the IEEE-VPPC'*17*, and a grant that covered all expenses related to the participation and attendance to IEEE-VPPC'*17* (conference registration, transport, hotel, etc.).

- First prize: up to a limit of *3000 US$;*
- Second prize: up to a limit of *1500 US$.*

From a participation survey, all the participants were interested by the open-ended program (available models, Matlab Simulink^{TM} program, etc.). *80 %* was also motivated by the competitive nature of the proposed challenge. Participate to an international challenge to compare their work on a common subject and criteria then appears as a motivation for many researchers.

Figure 7 *World map participation (world map from* commons.wikimedia.org*)*

Results and discussion

The ten best participant strategy costs are compared in figure 10. The FC degradation $\$\Delta_{fc}$, the battery degradation $\$\Delta_{bat}$, the H_2 consumption $\$_{H2}$ and the final battery charge cost $\$_{charge}$ are differentiate from the global cost $\$_{global}$. Some participant strategies are close to the theoretical DP optimum of *1.612* US$ (green chart). The best EMS allows to perform the scoring driving cycle of figure 6d with a global cost of *1.624 US$* (*+ 0.73%*) compared to *1.629 US$* (*+ 1.05%*) for the second. The cost differences at the leader group are very low because the cost distribution is quite similar than for the DP optimal strategy (figure 8 and figure 10). Here, the H_2 consumption represents *82 %* of the trip cost. However, even if the fuel consumption during a trip is an important part of the global cost, it is not the major key issue of a competitive EMS (table 2). Indeed, low consumptions during a trip are not related to the best strategies. For example, the best strategy allows to consume *10.34* gH_2/km during the scoring trip compared to only *8.14* gH_2/km for the *8*th strategy. However, this consumption does not consider the additional related battery charging H_2 consumption. The final battery charging cost $\$_{charge}$ appears as a major key issue in the EMS development (yellow part in figure 10 and table 2). In a general way, lower is the final battery *SoC*, higher is the global cost because maintain a low *SoC* 1) degrades the battery during the trip and 2) requires to charge the battery with a high current of *248* A at the end of the trip, which corresponds to the best FC efficiency point. This is related to additional battery and FC degradations (figure 9). This means that keeping a high battery *SoC* during the driving cycle will ensure a low charge cost at the end, and then a low global cost. This also reduces the battery degradation (table 2). The *9*th strategy respects this criterion. However, its global cost is high (*2.37 US$*) because of several FC start/stop events. This increases the FC degradation and reduces its lifetime to *488* h. In this way, considering a repetitive sequence of the scoring cycle, the FC can operate *2,656* h with a well-designed EMS. This must be balanced with the battery lifetime to perform a competitive EMS (table 2).

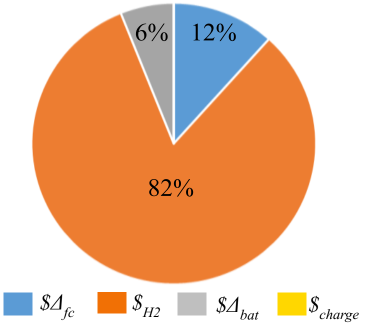


Figure 8 *Optimal cost distribution*

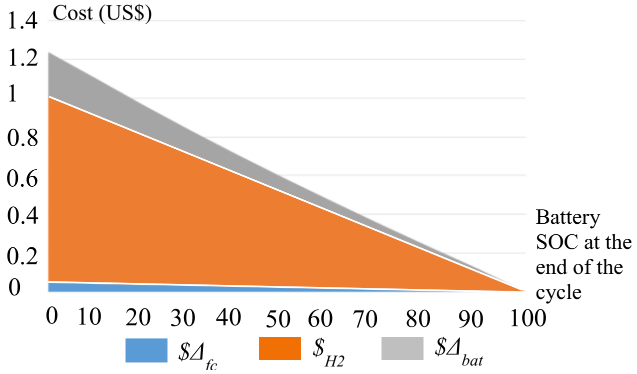


Figure 9 *Detailed battery charging cost*

All the EMSs are based on heuristic strategies to reduce the H_2 consumption and the source degradations. Based on the challenge specification and on their expertise, the participants designed their strategies from various inputs and heuristic rules [15]-[19]. The best strategy maintains the battery SoC at it maximal value while the FC operates at its maximal efficiency and lower degradation operating [15]. [16] and [17] (4th and 5th positions) use similar concepts to build their EMSs but they do not reach such good results because they neglect the battery SoC effect on the battery degradation. The second best strategy extracts comprehensive rules from optimized results of twelve typical driving cycles [18]. The third best EMS defines the most suitable FC reference current depending on the battery SoC and the traction power by means of a look-up table [19]. The challenge participants then had to find an acceptable compromise between the H_2 consumption and the source's degradations without any information about the future scoring driving cycle. This is the most interesting issue that the challenge participants faced during the competition. Look-up tables, relays, fuzzy logic functions or genetic algorithm are then combined to design the EMS depending on the battery *SoC*, the FC voltage, FC current, the traction reference force, etc. In this way, even if the developed strategies are different and sometimes complex, it did not take much time for competitors to achieve competitive results. From a participation survey and considering the challenge deadlines, participants have, on average, spent between *10* to *30* days to develop their strategies. This time period is relatively short, considering that participants had to assimilate a simulation program and the organization formalisms (i.e. EMR).

It is possible to conclude that, with a good expertise and a good knowledge of the system, one comes to efficient on-line managements and this, rather quickly. For example, based on the proposed models, it appears that maintaining a high battery *SoC* is an important key issue to reduce the global trip cost. On the other hand, the influence of management remains predominant and a bad analysis of the system can quickly result in high cost (e. g. EMS from the *9*th participant).

Conclusion

An international challenge devoted to the energy management of a fuel cell/battery vehicle was launched in October *2016* during the IEEE-VPPC'*16*, in Hangzhou, China. In total, *48* participants from *14* different countries took part in this challenge. It has rewarded the best EMSs based on a common vehicle and specifications. The vehicle driving cost, which includes the hydrogen and the source degradation costs, was used as a base of comparison. For example, the best strategy passed through the scoring driving cycle for an overall cost of *1.62 US$* against *2.98 US$* for the tenth (+ *84* %). In this way, well designed EMS may lead to reduce significantly the trip cost while ill-designed EMS may lead to high fuel consumption or premature source degradations.

Tight deadlines have deliberately limited the development times, but the best results are close to the theoretical dynamic programming optimum. Thus, although the developed strategies are different and sometimes complex, it did not take much time for participants to achieve competitive results. Knowing in advance the mission profile also does not appears so important because the best developed strategies have quite similar results than for the DP optimal strategy.

The top scoring participants have been distinguished and presented their results in a special session at the IEEE-VPPC'*17* in Belfort, France. *7* papers were presented. This special session was also an opportunity to present the second IEEE VTS Motor Vehicles Challenge *2018* focused on the energy management of a Range Extender Electric Vehicle, the Chevrolet Volt [20].

Rank	$global (US$)	Battery lifetime (h)	FC lifetime (h)	Cons. (gH_2/km)	Final battery SOC
Opt	1.612	4703	2447	10.34	1
1	1.624	6147	2382	10.44	0.98
2	1.629	6316	2372	10.33	0.96
3	1.647	6290	2278	10.39	0.96
4	1.656	4903	2486	10.20	0.94
5	1.658	3771	2476	9.48	0.86
6	1.716	3113	2656	8.30	0.67
7	1.728	3952	2215	9.28	0.78
8	1.892	2235	2352	8.14	0.56
9	2.370	5397	488	9.96	0.93
10	2.982	1928	2005	14.9	0.56

Table 2 *Global results*

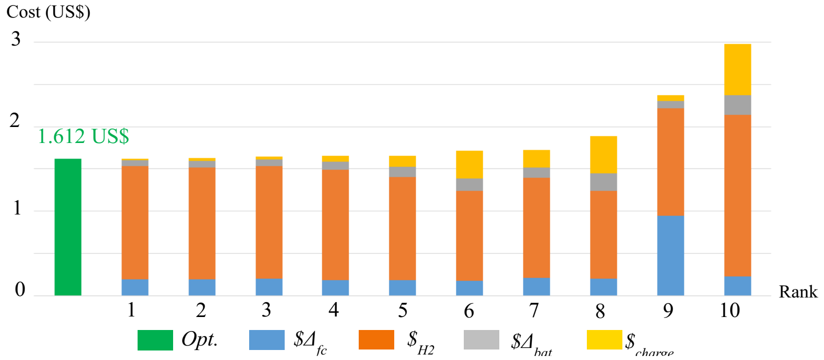


Figure 10 *Best scoring driving costs*

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In 2015, Loïc Boulon was general chair of the IEEE-Vehicular Power and Propulsion Conference in Montréal (QC, Canada). Prof. Loïc Boulon is VP-Motor Vehicles of the IEEE Vehicular Technology Society and he is the holder of the Canada Research Chair in Energy Sources for the Vehicles of the future.

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