IEEE VTS Motor Vehicles Challenge 2020 - Energy Management of a Fuel Cell/Ultracapacitor/Lead-Acid Battery Hybrid Electric Vehicle

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***Abstract*—This paper proposes a challenge focused on the energy management of a Fuel Cell/Ultracapacitors/Battery Vehicle. Both Academic and Professional teams are welcomed to participate in this challenge. The aim of this challenge is to develop a robust Energy Management Strategy to increase the energy sources' lifetime and to minimize the hydrogen consumption. In this way, the simulation model and control presented in this paper will be provided to the challenge participants (downloadable Matlab Simulink file). The top scoring participants will be distinguished and invited to present their results in a special session at the 2020 IEEE VPPC.**

***Keywords*—hybrid electrical vehicles, ultracapacitors, fuel cells, energy management**

I. Introduction

Since 2016, the IEEE Vehicular Technology Society (VTS) proposes to participate each year, during the annual conference IEEE-VPPC, at an international challenge devoted to the Energy Management Strategy (EMS) of different hybrid electric vehicles (HEV). The first edition of the IEEE VTS motor vehicles challenge, launched in October 2016 at Hangzhou in China. The challenge dealt with a fuel cell vehicle with battery [1]. The challenge received solutions from 48 industrial and academic participants from 14 countries. The winner solution based on a fuzzy logic controller was presented by a team from Universidad de Rio Cuarto in Argentina [2].

The second edition, launched in December 2017 at Belfort in France, was dedicated to a range extender vehicle [3]. For this edition, solutions were received from 92 industrial and academic participants from 16 countries. An adaptive EMS based on Pontryagin's minimum principe proposed by researchers from the Hanyang University in South Korea was the winner solution [4]. The third edition of the challenge, launched in August 2018 at Chicago, USA focused on the energy management of a dual-mode locomotive [5]. The results obtained with the EMS presented in [6] a rule-based strategy based on the Ragone plot outperformed all the solutions proposed by 45 teams from 15 countries.

The fourth edition of the IEEE VTS motor vehicles challenge is organized by the Universidad Industrial de Santander, Colombia, the University of Bourgogne Franche-Comté, France, the University of Quebec at Trois-Rivieres and the Universidad Nacional de Rafaela, Argentina. It is focused on a HEV called ECCE illustrated in Figure 1.

ECCE is a modular-mobile laboratory used to evaluate under real conditions the electric components of Hybrid Electrical Vehicles. For the IEEE VTS motor vehicles challenge 2020 purpouses, ECCE is powered by a 30kW PEM fuel cell, 540 V 16 F ultracapacitors and a 540V battery pack. The FC, the UC and the traction motors are connected to a 540 DC bus via power converters and the battery is directly connected to the DC bus as presented in Figure 2.

Fig. 1. ECCE HEV

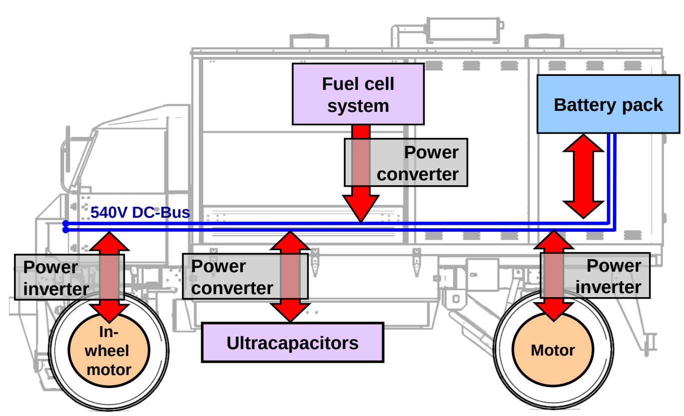


Fig. 2. Structural scheme of the studied vehicle

The participants in the challenge must define a global EMS considering the characteristics and constraints of each energy source. The solutions must respect constraints in the DC bus voltage, UC and batteries SOC. They will be evaluated using a multi-objective function $€_{tot}$ composed of six cost functions to minimize:

1) the hydrogen consumed $€_{H_2}$,
2) the FC cost considering its degradation $€_{fc}$,
3) the SC cost considering its degradation $€_{sc}$,
4) the battery cost considering its degradation $€_{b}$ and
5) the battery recharge at the end of the cycle $€_{sust}$

The ECCE HEV model and its control will be provided to the participants using MATLAB-Simulink software. Both industrial and academic teams are welcomed to propose their own EMS. Two power profiles are provided to evaluate the EMS. However, the solutions will be scored using a third secret profile. The participants will be invited to attend the 2020 IEEE VPPC conference.

This paper is organized as follows: Section II introduces the studied vehicle and its power sources models. Section III presents the cost function. Section V presents the conclusions and outlooks.

II. ECCE

The French Army (DGA) has designed and constructed the Electrical Chain Components Evaluation vehicle (ECCE). It is a mobile laboratory to evaluate under real conditions the electric components of Hybrid Electrical Vehicles (HEVs) that reduce the energy consumption and the pollution emission of conventional vehicles. ECCE permits evaluating different energy sources such as batteries, fuel cells, internal combustion engines, ultracapacitors or flywheels. Previous research about ECCE is presented in [7]–[16]

A. Fuel Cell

ECCE test bench is equipped with a PEMFC stack. The FCS was developed by HELION, (Aix-en-Provence, France), for the SPACT-80 project which aimed to develop FCS suitable for high power transport applications: the LHyDIE hybrid locomotive [17] and the ECCE hybrid vehicle. It is illustrated in Figure 3, their characteristics are resumed in Table I.

B. Lead-acid batteries

ECCE test bench is equipped with a bank of 46 valve-regulated lead-acid batteries in series connection. Table II resumes the parameters of the lead acid batteries and Figure 4 illustrates the batteries implemented in ECCE.

C. Ultracapacitors

ECCE is equipped with 2 ultracapacitor banks developed by SAFT (Bordeaux, France) in cooperation with the GREEN research laboratory (Nancy, France) [18]. Figure 5 shows the UC implemented in ECCE test bench and Table III resumes the UCS characteristics.

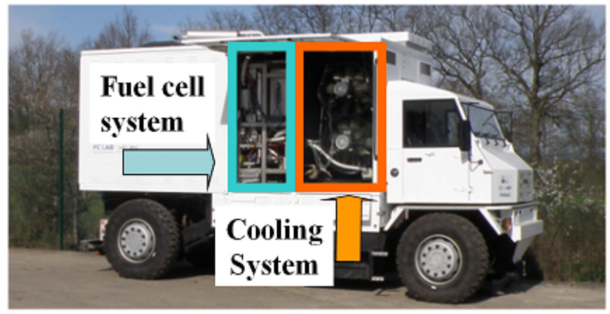


Fig. 3. Fuel cell system implemented in ECCE

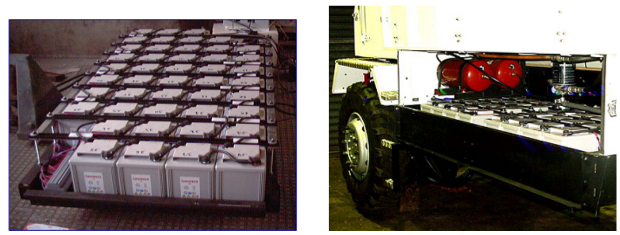


Fig. 4. Lead-acid batteries implemented in ECCE

Fig. 5. SAFT ultracapacitors implemented in ECCE

TABLE I. ECCE FUEL CELL SYSTEM PARAMETERS

Description	Value
Supplier	HELION (Areva)
Elements in series	2*110
Maximal gross power	80 [kW]
Maximal voltage	190 [V]
Power rate change	5 [A/s]

TABLE II. ECCE BATTERIES PARAMETERS

Description	Value
Fabricant	Hawker
Technology	Lead-acid
Elements in series	46 (12[V])
Nominal voltage	552 [V]
Capacity	72 [Ah]

TABLE III. ECCE ULTRACAPACITOR SYSTEM PARAMETERS

Description	Value
UC Fabricant	SAFT
DC/DC Converter supplier	CIRTEM
UC in series	216 (2.5 [V] - 3500 [F])
UC Rated current	600 [A]
DC/DC converter rated current	200 [A]
UC Rated voltage - capacitance	540 [V] - 16 [F]

D. Models

To simplify the simulation model and control strategy, a polarization curve is selected to model the fuel cell stack as done in previous challenges [5], [19]. The UC model presented by [20] is considered using the parameters of the equivalent circuit experimentally found in [16]. The batteries model presented by [21] is considered using the parameters of the equivalent circuit found in [9].

E. EMR

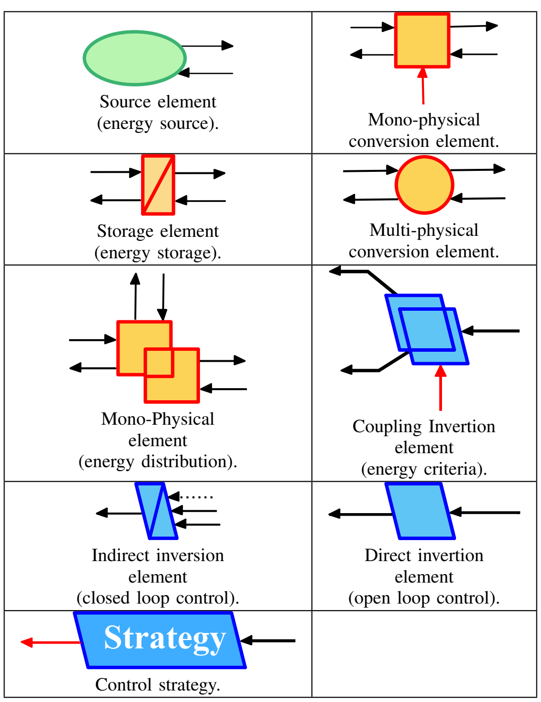
The energetic macroscopic representation EMR is a synthetic graphic tool for the systematic analysis of the interactions between subsystems in multi-physics systems. The pictograms presented in Table IV are used to represent the elements are interconnected following the action–reaction principle and respecting the integral causality. Each pictogram is internally described using transfer functions, mathematical relations or another modelling tool. The instantaneous exchanged power is the product between action and reaction variables, represented by arrows (inputs and outputs). The system control structure is deducted by direct inversion of the EMR.

The EMR is frequently used to study multi-physics systems with multi-sources [22], [23], hybrid electric vehicles, [24] or photo-voltaic generation systems [25], among others. The EMR has also used in previous IEEE VTS motor vehicles challenges [5], [19].

F. Simulation Model

The simulation model is implemented in Matlab Simulink using the Energetic Macroscopic Representation formalism. Figure 6 illustrates the EMR of the ECCE vehicle and its implementation in Matlab Simulink.

TABLE IV. EMR PICTOGRAMS.



III. EVALUATION OF THE SOLUTIONS

The participants must propose Energy Management Strategies (EMS) to define the power distribution between the available power sources as defined in Equation 1.

The power consumed by the motor drives and the ancillary P_{tract} is not known a priori. The EMS must define in real-time power references for the fuel cell P_{fcs}, the supercapacitors P_{scs} and a braking resistor brake P_{rb}. The power supplied by the batteries P_{bat}, cannot directly controlled because they are directly connected to the DC bus without a power converter.

$$P_{trac} + P_{rb} = P_{fcs} + P_{bat} + P_{scs} \tag{1}$$

The participants must define reference currents for the fuel cell, the ultracapacitors and the braking resistor. One challenge to consider, is that the power supplied by each source depends on the DC bus voltage which strongly depends on the batteries current.

The solutions will be evaluated considering a multi-objective cost function. The cost considers the cost associated to the degradation of the sources (FC, UC and batteries) and the cost of the energy consumed (hydrogen and electricity to recharge the energy storage sources). The degradation of the sources is taken into account by a depreciation cost. Degradation functions $\Delta_{\mathrm{X}}(\mathrm{t})$, with X the considered sources are provided. A value of 0 and 1 will respectively correspond to the beginning and end of the considered sources life. The energy of the sources corresponds to the cost of the total hydrogen and electricity required to complete the profile and to recharge the ESS at the end of the profile. The considered cost functions are presented below:

A. Hydrogen consumption

The hydrogen operational cost is calculated by taking into account the hydrogen consumption:

$$€_{H_2}(t) = \frac{H_{2-cost}}{1.10^3} \int_0^t \dot{m}_{H2}(t)dt \tag{2}$$

with $\dot{m}_{H2}(t)$ the hydrogen mass flow (g/s) and H_{2-cost} the hydrogen cost per unit of hydrogen mass (€/kg) based on the projection of 2020 [26].

B. Degradation of the fuel cell

The degradation function $\Delta_{fc}(t)$ depends on the power operation $p_{fc}(t)$ and the start number N_{start} of the fuel cell [27], [28]:

$$\Delta_{fc}(t) = N_{start}\Delta_{start}(t) + \int_0^t \delta(t)dt \tag{3}$$

$$\delta(t) = \frac{\delta_0}{3600}\left(1 + \frac{\alpha}{P_{fc-rat}^2}\left(p_{fc}(t) - P_{fc-rat}\right)^2\right) \tag{4}$$

with $\Delta_{\text{start}}(t)$ the start-stop degradation coefficient, δ_0 and α load coefficients and P_{fc-rat} the rated power of the fuel cell (W). The fuel cell is considered as ON when its current $i_{fc}(t)$ will be greater than 0 A. The operational cost of the fuel cell can then be deduced from $\Delta_{fc}(t)$.

$$€_{fc}(t) = \frac{P_{fc-rat}}{1.10^3} FC_{cost}\Delta_{fc}(t) \tag{5}$$

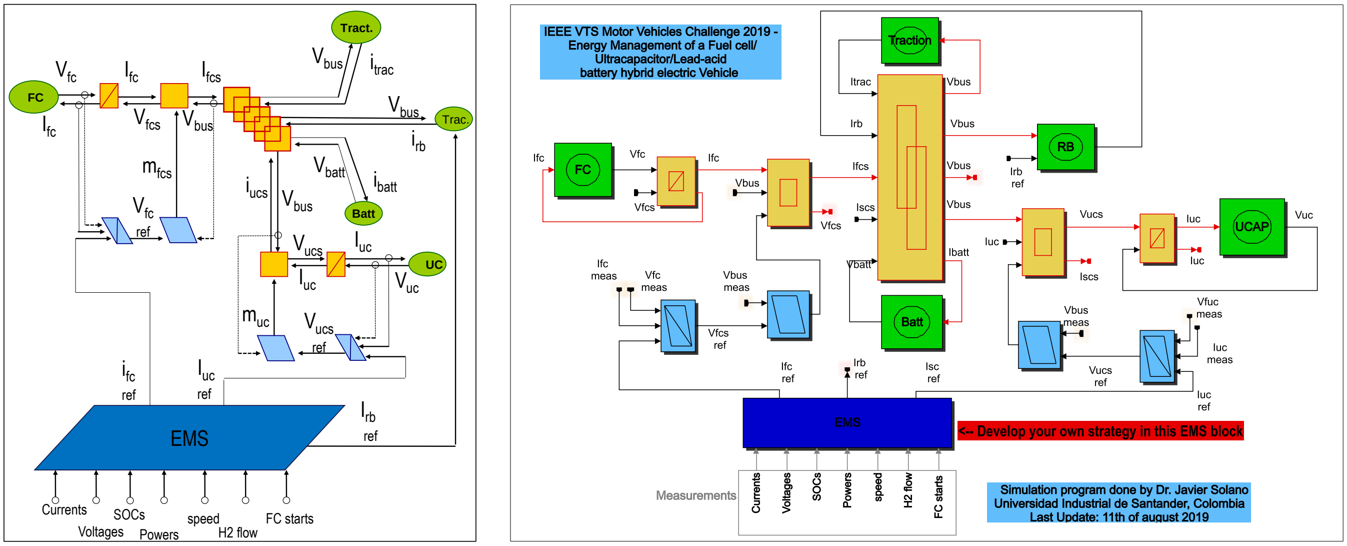


Fig. 6. ECCE EMR - ECCE EMR implemented in Simulink (downloadable file)

with FC_{cost} the fuel cell cost per unit of power (€/kW), which is based on the target of the department of energy (DOE) of the USA [29].

C. Degradation of the ultracapacitors

The lifetime of the supercapacitors is expected to be 30000 h. The degradation function of the supercapacitors $\Delta_{sc}(t)$ is calculated by the ratio between the use time t_{use} and the expected lifetime:

$$\Delta_{sc}(t) = \frac{t_{use}}{30.10^3} \tag{6}$$

The operational cost of the supercapacitors can then be deduced from $\Delta_{sc}(t)$:

$$€_{sc}(t) = E_{sc-rat} SC_{cost} \Delta_{sc}(t) \tag{7}$$

with E_{sc-rat} the rated energy of the supercapacitors (kWh) and SC_{cost} the supercapacitors cost per unit of energy (€/kWh).

D. Degradation of the batteries

The lifetime of the battery is expected to be the half of the lifetime of the supercapacitors, i.e. 15000 h for 7.5 years. The battery degradation function $\Delta_b(t)$ depends of the state of charge with $f\left(SOC_b\right)$ and power dynamics with $g\left(i_b\right)$ [29]:

$$\begin{aligned} &\Delta_b(t) \\ &= \tfrac{1}{3600.15 \cdot 10^3 \cdot Q_{b-rat}} \int_0^t \left| f\left(SoC_b\right) \cdot g\left(i_b\right) \cdot i_b(t) \right| dt \end{aligned} \tag{8}$$

with Q_{b-rat} and i_b respectively the rated capacity (Ah) and the current (A) of the battery. The operational cost of the battery can then be calculated from $Delta_b(t)$:

$$€_b(t) = E_{b-rat} B_{cost} \Delta_b(t) \tag{9}$$

with E_{b-rat} the rated energy of the battery (kWh) and B_{cost} the battery cost per unit of energy (€/kWh).

E. Recharge of the batteries at the end of the cycle

To have a fair scoring of the EMS, the final SoC of the battery and supercapacitors should be the same for each participant. A charge sustaining process is then needed to sustain the SoC. A positive or negative penalty $€_{sust}$ will be then used to sustain the ESS using the network.

$$€_{\text{sust}}(t) = \frac{N_{cost}}{1.10^3} \left(\eta_{dc-b-avg} \cdot E_{b-end} + \eta_{dc-sc-avg} \cdot E_{sc-end}\right) \tag{10}$$

with $\eta_{dc-b-avg}$ and $\eta_{dc-sc-avg}$the average value of the efficiency maps of the boost choppers; and E_{b-end} and E_{sc-end} the energy stored of the battery and supercapacitors at the end of the simulation (kWh). Negative and positive penalties mean respectively that the ESS has been too charged and discharged during the simulation.

F. Total cost

The total cost to minimize $€_{tot}$ can then be defined as:

$$€_{tot} = €_{H_2} + €_{fc} + €_{sc} + €_b + €_{sust} \tag{11}$$

G. Constraints

The DC bus voltage, the batteries and UC SOC and the fuel cell current must remain between predetermined bounds.

H. Design and evaluation of solutions

Figure 7 illustrates two power profiles provided to the participants to develop and to evaluate their EMS. All proposed participant EMS will be, however, scored with an unknown speed profile.The challenge issue is then to propose a real-time optimization based-EMS.

IV. Conclusion

This paper proposes the framework for the IEEE VTS motor vehicles challenge 2020. Participants will be invited to respond to this challenge by following the participation procedure describes in the IEEE VTS Challenge website: http://www.uqtr.ca/VTSMotorVehiclesChallenge2020

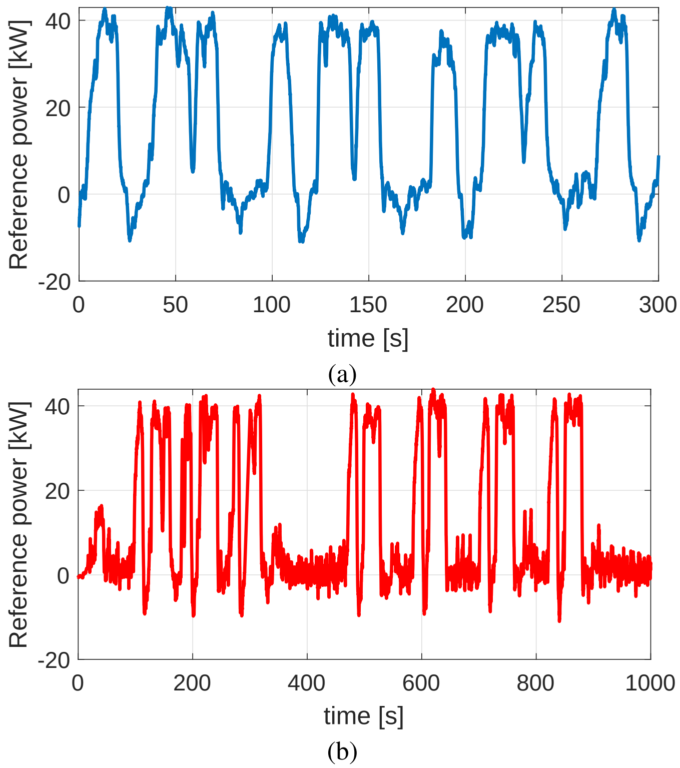


Fig. 7. Power Profiles for the EMS development

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