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Power Hardware-In-the-Loop simulation for testing multi-source vehicles

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Abstract: Energy management of multi-source vehicles is a complex task. The higher the number of sources becomes, the higher the complexity is. Moreover, the energy management strategies have to face real-time issues. As a consequence, it is important to find some testing procedures to assess the developed strategies, in real-time conditions before implementation in the vehicle. In this paper, a Power Hardware-In-The-Loop simulation is implemented for a Fuel Cell – battery – Supercapacitors vehicle. The set-up enables to test some Energy Management Strategies in real-time conditions.

Keywords: hardware-in-the-loop, energy management, supercapacitor, battery, fuel cell, vehicle

LIST OF ABREVIATIONS

EMR	Energetic Macroscopic Representation
EMS	Energy Management Strategy
ESS	Energy Storage System
FC	Fuel Cell
H-ESS	Hybrid Energy Storage System
P-HIL	Power Hardware-In-the-Loop
SC	SuperCapacitor
SoC	State of Charge

I. INTRODUCTION

The urban travel demand is significantly growing. According to the International Energy Agency the 2012 concentration of CO_2 was about 40% higher than in the mid-1800s (IEA, 2013). It is then important to find out alternatives to conventional thermal vehicles.

Several solutions have been depicted such as battery electric vehicles or Fuel Cell (FC) vehicles (Chan et al., 2010). However, each solution has some limitations. FCs have some power transfer issues (Bernard et al., 2009) while batteries have some lifetime issues (Omar et al., 2014). Multi-source vehicles represent an interesting alternative as they enable to take advantage of the properties of the different sources (Ehsani et al., 2009). However, they represent very complex systems. It is then difficult to manage such systems.

Several works has been done on Energy Management Strategies (EMSs) of multi-source vehicles. Two approaches have been depicted (Salmasi, 2007; Wirasingha and Emadi, 2011), rule-based approach (García et al., 2013; Thounthong et al., 2009) and optimization-based approach (Yu et al., 2011; Odeim et al., 2016). The main issues are related to real-time applications. Moreover, the EMSs have to ensure the physical limitations of the sources for any driving condition. As a consequence, it is important to find testing procedures to assess the EMSs before their implementation in a real vehicle.

Power Hardware-in-The-Loop (P-HIL) simulation (Bouscayrol, 2011) has been used in several applications for testing components before their implementation in a real system. P-HIL has thus been used for testing EMSs of hybrid and electric vehicles in real-time conditions (Allègre et al., 2013; Castaings et al., 2015; Odeim et al., 2015).

The objective of this paper is to present a P-HIL simulation of a FC-battery-Supercapacitors (SCs) vehicle. The developed set-up enables to assess an EMS in real-time conditions (e.g. various driving conditions). The control organization of the P-HIL simulation is achieved by using Energetic Macroscopic Representation (EMR) (Bouscayrol et al., 2012). The second section is devoted to the description of the P-HIL simulation. The control organization is presented in the third section. The results are given in the last section before the conclusion.

II. P-HIL SIMULATION OF THE STUDIED SYSTEM

A. P-HIL principle

Hardware-In-the Loop simulation consists in adding some actual elements (hardware) in the simulation loop (Bouscayrol, 2011). In Power HIL, some power elements can be tested before their implementation on the real system. It is useful for testing the subsystem and its control in real-time conditions. (Figure 1.a). In P-HIL simulation, the power part is split into two parts, the part under test (with its control) and the emulated part. An interface (interf. in Figure 1.a) is required for connecting the simulation signals and the power signals. The interface has then power and signals elements. (Figure 1.b). The emulation system must have the same behavior than the simulated system. The control references of the emulation system come from the real-time simulation of the emulated

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system. Also, the interface must be faster than the emulated system to emulate without delay.

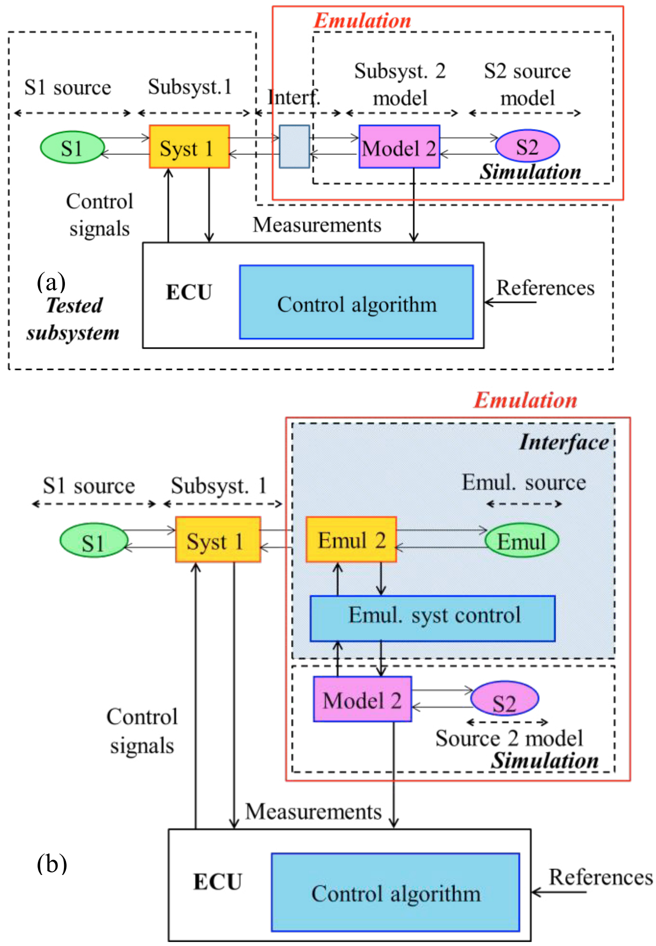

Figure 1: P-HIL, (a) principle, (b) practical scheme

B. Application to a FC-battery-SCs vehicle

Studied system

Several architectures have been used in the literature for FC-battery-SCs associations (Li et al., 2012; Solano-Martinez et al., 2011; Zandi et al., 2011). The architecture of the studied vehicle is presented in Figure 2. Each source is interfaced using a DC-DC converter. It enables the decoupling between the DC bus voltage and the different sources (Amjadi and Williamson, 2010).

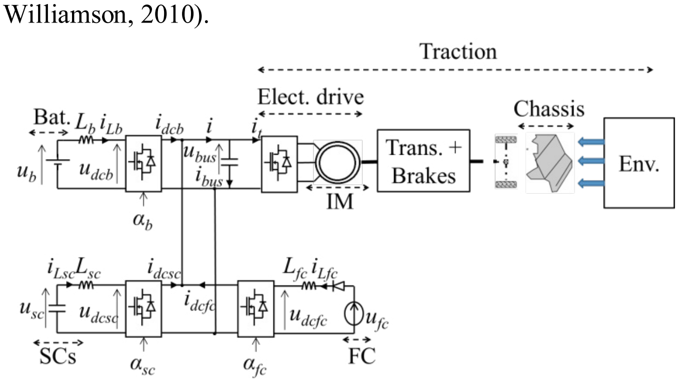

Figure 2: Architecture of the studied vehicle

P-HIL organization

The objective of the P-HIL simulation is to assess the system controllability in real-time and to validate the FC and SCs behavior. In the presented work, the emulated parts are the battery branch and the traction part. The corresponding emulation systems are depicted in Figure 3. For the battery branch, the battery is replaced by a SCs bank. The SCs bank has to reflect two battery characteristics

- the battery SoC limitations : this depends on the SCs bank size
- the battery voltage dynamics. The SCs voltage has higher dynamics than the battery voltage ones. If the battery model is accurate enough, the battery voltage dynamics can be reflected by the SCs.

The traction part is emulated by a current source composed of a DC-DC converter, a smoothing inductor and a SCs bank. The main dynamics of the inverter current are taken into account in the traction model (cf. section III).

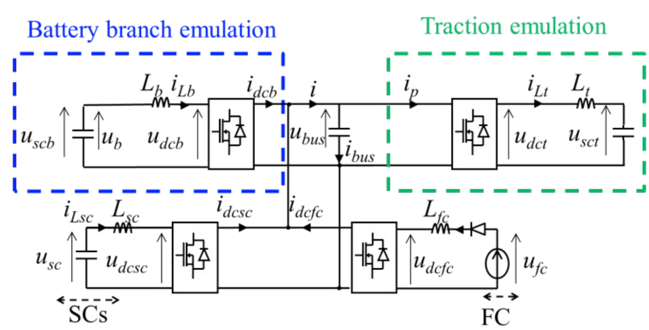

Figure 3: P-HIIL system architecture

The next part is devoted to the control organization of the P-HIL system. Different parts have to be interconnected. Indeed, there are the models to be simulated, the emulation subsystems with their control, the tested subsystems and their control. A graphical formalism, Energetic Macroscopic Representation (EMR) is used as a tool for the interconnection of subsystems. First, EMR is based on action-reaction principle. It enables to ensure a physical connection between the elements. Second, EMR approach is based on causality principle. It enables to systematically deduce the control structure of the system and to use real-time models for the emulation subsystems. More details are given in (Bouscayrol et al., 2012).

III. CONTROL ORGANIZATION

A. Real part

The control of the system is achieved by using Energetic Macroscopic Representation (EMR). EMR highlights energetic properties of the components of a system to develop control schemes (Bouscayrol et al., 2012). There are several pictograms to represent the system model (see Appendix). By using EMR approach, the control part is organized in two levels, the "local control" part and the "global control" part (i.e. EMS). The main interest of using EMR is that the "local control" part of the system can be systematically deduced by "mirror" effect from its EMR. The EMR and the control part of the "real part" of the system are depicted in Figure 4.

Local control part

The local control is represented by the light blue blocks in Figure 4. It manages the system components to track the reference of the DC bus voltage. The right duty cycles of the converters (α_b, α_{fc} and α_{sc}) are then defined. In addition, the local control points out the control requirements. In the studied case 4 sensors and 4 controllers (closed-loop control) are required as well. The inversion of an accumulation element is performed via a closed-loop control (crossed blue parallelogram). A conversion element is directly inverted with an open-loop control (blue parallelogram). The inversion of a coupling element depicts degrees of freedom that correspond to the output of the EMS (global control).

Global control part

The global control part corresponds to the Energy Management Strategy (EMS). That aims to use the degrees of freedom of the control in the best way. There are two kinds of EMSs for multi-source vehicles; rule-based EMSs and optimization-based EMSs (Salmasi, 2007)

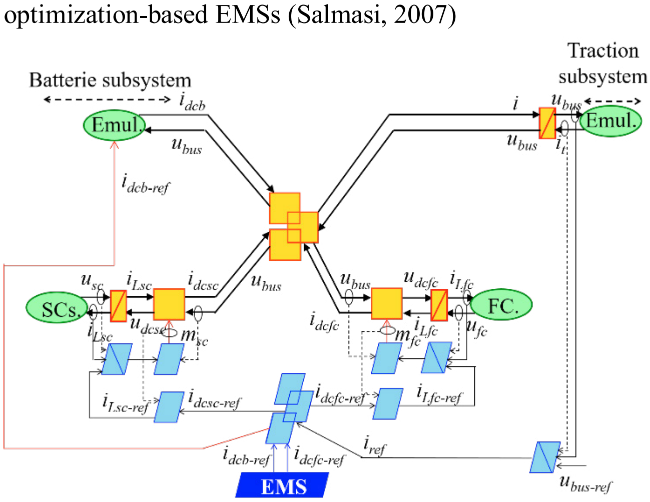

Figure 4: EMR and control organization of the "real part"

B. Emulated parts

The EMR and its control organization of the emulated parts are depicted in Figure 5. The purple blocks correspond to the simulated part of the P-HIL simulation. As it can be noticed that the control references come from the simulation of the real components models (purple pictograms). Also this is a reduced-scale P-HIL simulation. As a result, some adaption coefficients are taken into account (Allègre et al., 2013). These coefficients enable to pass from the full-scale simulated models to the reference signals of the reduced-scale system (1). The reduced-scale coefficients values are given in Table 1.

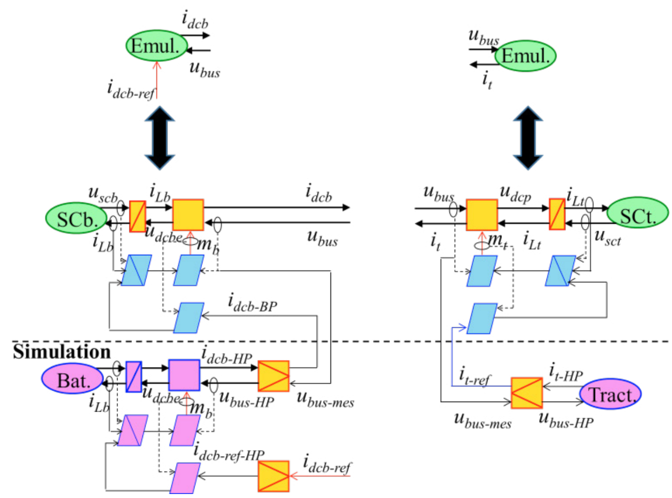

Figure 5: EMR and control organization of the emulated parts

$$\begin{cases} i_{dcb-BP} = \dfrac{i_{dcb-HP}}{k_{i-Sbat}} \\ i_{dcb-ref-HP} = i_{dcb-ref} k_{i-Sbat} \\ u_{bus-HP} = k_{u-Sbat} u_{bus-mes} \\ i_{t-ref} = \dfrac{i_{t-HP}}{k_{i-tract}} \end{cases} \quad (1)$$

IV. VALIDATION OF AN ENERGY MANAGEMENT STRATEGY

A. Principle

The experimental set-up is presented in Figure 6. A dSPACE 1005 controller board is used as an interface between the power part and the computer board. The EMS is an optimization-based strategy. It consists in minimizing the hydrogen consumption while improving the battery lifetime (Castaings et al., 2016). The first test is achieved on a standard driving cycle (WLTC class 2, low velocity phase, Figure 7) where the EMS parameters have been identified. This corresponds to "ideal" driving conditions. The second test is carried out using a real driving cycle (Figure 8) coming from results on the instrumented car (Tazzari Zero) (Depature et al., 2014). This test enables to assess the robustness of the EMS when varying the driving conditions. The parameters of the full scale and reduced scale systems are given in Table 1.

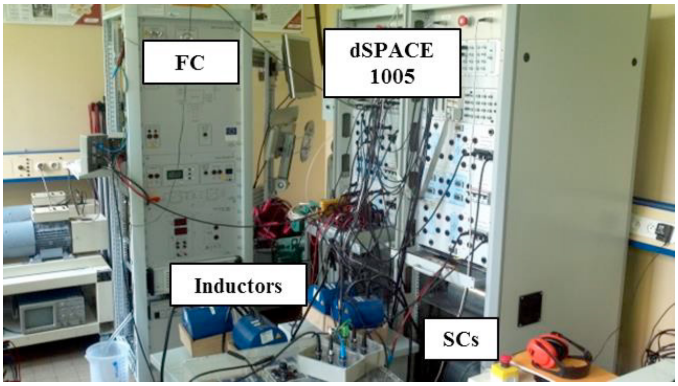

Figure 6: Experimental set-up

Table 1: Full scale and reduced scale systems parameters

	Full-scale system	Reduced-scale system
FC stack	Type: PEMFC Max power: 20 kW Voltage range: 50-80 V Max current : 360 A	Type: PEMFC Max power: 1.2 kW Voltage range: 28-43 V Max current: 45 A
Vehicle	640 kg	$k_{i\text{-}tract}$=1/17
Electric drive	Rated voltage: 80 V Rated power : 15 kW	Rated voltage: 80 V Rated power : 882 W
Smoothing inductors	SCs :r_{Lsc}=10mΩ | L_{sc}=200µH FC: r_{Lfc}=10 mΩ | L_{fc}=200µH Battery : r_{Lb}=10mΩ | L_b=200µH	SCs :r_{Lsc}=260mΩ | L_{sc}=861µH FC: r_{Lfc}=200 mΩ | L_{fc}=839µH Battery : r_{Lb}=100mΩ | L_b=882µH
SCs bank	45 V |R_{sc}=3.8 mΩ | C_{sc}=290 F $u_{sc\text{-}M}$=45 V | $u_{sc\text{-}m}=0.65u_{sc\text{-}M}$ $u_{SC\text{-}0}=0.9u_{sc\text{-}M}$	45 V | R_{sc}=57 mΩ | C_{sc}=19 F $u_{sc\text{-}M}$=44 V | $u_{sc\text{-}m}=0.65u_{sc\text{-}M}$ $u_{SC\text{-}0}=0.9u_{sc\text{-}M}$
Battery	24 cells (3.3 V / 20 Ah / 820 W) $SoC_{b\text{-}M}$=100 % | $SoC_{b\text{-}m}$=90 % $SoC_{b\text{-}0}$=95 %	$k_{i\text{-}sbat}$=1/17 $k_{u\text{-}sbat}$=1

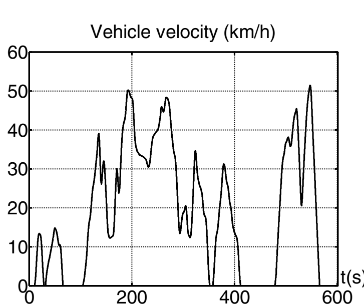

Figure 7: standard driving cycle

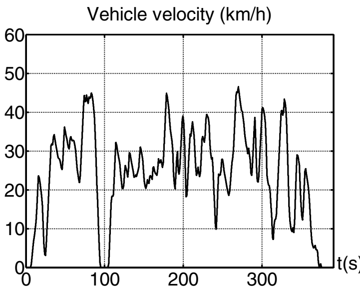

Figure 8: real driving cycle

B. Standard driving cycle

Some experimental results on the standard driving cycle are given next. The EMS enables to reduce the FC current peaks. This is interesting for its lifetime (Figure 9). As depicted in Figure 10 the EMS enables to respect the SCs voltage limitations. This is important for ensuring the system safety. This aspect has been assessed thanks to the P-HIL set-up.

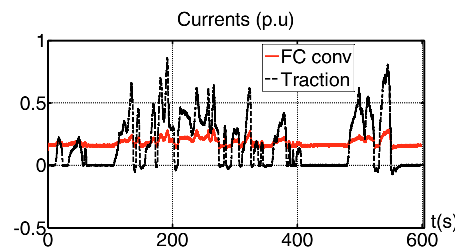

Figure 9: FC branch and traction currents

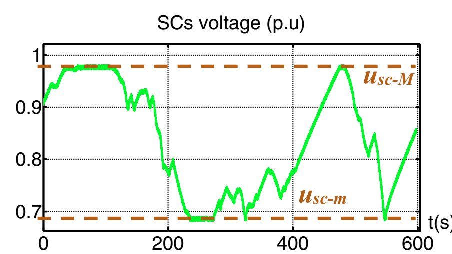

Figure 10: SCs voltage

C. Real driving cycle

The same trends can be noticed for the real driving cycle (Figure 11 and Figure 12). The key point is that the EMS still enables to reach interesting performances while ensuring the system safety. However, as the parameters were not computed on this driving cycle, the SCs tend to be discharged at the end of the driving cycle. This can cause some repeatability issues. Indeed, if the same driving cycle is repeated, the results will not be the same as the previous one.

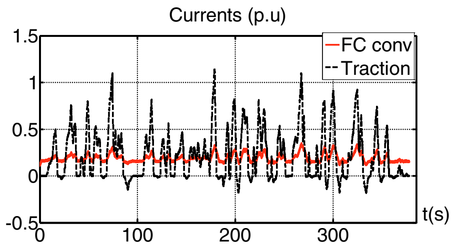

Figure 11: FC branch and traction currents

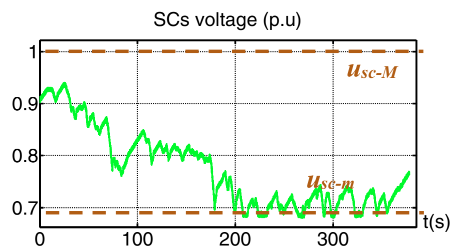

Figure 12: SCs voltage

V. CONCLUSION

A Power Hardware-In-the-Loop Simulation has been developed for a Fuel Cell – battery –Supercapacitors vehicle. The traction part of the vehicle has been emulated by a current source. The developed set-up has enabled to test an Energy Management Strategy in real-time conditions. According to the results, the EMS proves to be effective for real-time applications.

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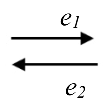
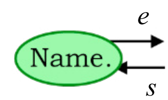
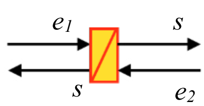
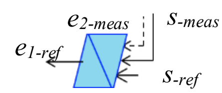
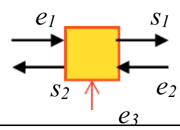
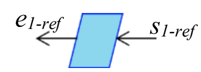
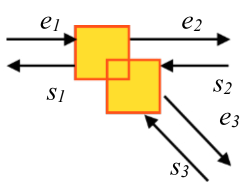
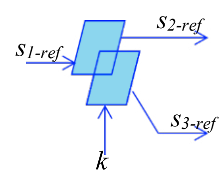
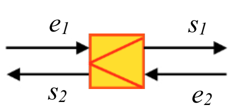
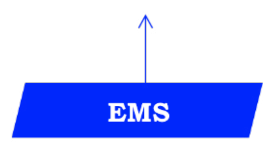
APPENDIX: PICTOGRAMS OF ENERGETIC MACROSCOPIC REPRESENTATION (EMR)

	Action and reaction variables $P = e_1 e_2$		Energy source
	Accumulation element (energy storage)		Indirect inversion (closed-loop control)
	Mono-domain conversion element		Direct inversion (open-loop control)
	Mono-domain coupling element (energy distribution)		Coupling inversion (energy criteria)
 $e_1 s_2 < s_1 e_2$	Power adaption		Energy Management Strategy