Practical Control Structure of a Heavy Duty Hybrid Electric Vehicle

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***Abstract*— This paper presents the Practical Control Structure (PCS) of a heavy duty hybrid vehicle. This PCS is based on both the Energetic Macroscopic Representation (EMR) and on the Maximal Control Structure (MCS). The power sources and energy sources of this vehicle are a fuel cell system, a supercapacitors system and lead acid batteries.**

Keyword- hybrid vehicle, modelling and simulation, energetic macroscopic representation, fuel cell system, supercapacitors, energy management.

I. INTRODUCTION

The Electrical Chain Components Evaluation vehicle (ECCE) is a 12 ton, 4 wheel drive mobile laboratory specifically designed for real-world evaluation of electrical components in military hybrid vehicles (Figure 1). This modular vehicle can be equipped with a variety of power and energy sources such as batteries, Fuel Cell System (FCS), Internal Combustion Engines (ICE), Supercapacitors System (SCS), and Flywheels System (FW). Although due to integration constraints all these devices are not simultaneously implemented on the vehicle. Previous literature has focused on the design [1], energy management [2], vehicle control [3] and modeling and simulation [4] of this test bench.

The aim of this paper is to present a tool not only to evaluate and compare energy management strategies but also to be implemented in the test bench. Those strategies require validation before implementation. The presented energetic architecture includes a fuel cell system, a supercapacitors system and lead acid batteries.

To represent this modular vehicle, the Energetic Macroscopic Representation (EMR) is used. The EMR and the different energetic configurations of the ECCE test bench have been presented in [4]. This paper is devoted to extend the EMR by including the Maximal Control Structure (MCS) and a Practical Control Structure (PCS) of the vehicle.

In the Section II of this paper an extended EMR of the vehicle, including the motocompressor group (MCG) used for air supply of the FCS is presented. Sections III and IV are devoted to the MCS and the PCS respectively. Finally, Section V presents some simulation results and analysis.

II. ENERGETIC MACROSCOPIC REPRESENTATION OF THE VEHICLE

The EMR is a synthetic graphic tool for the systematic analysis of all interactions between different elements (subsystems) of a multi physics system. Appendix A shows the pictograms used to represent the physical elements. These pictograms are interconnected following the action reaction principle and respecting the integral causality.

The EMR has several advantages: it allows the representation of multi physics systems, the systematic deduction of control structures, and the implementation is performed under Matlab Simulink environment. The EMR formalism has already been used in many real-world applications such as control of wind energy generation systems [5] or fuel cell control systems [6].

The generic EMR of a particular energetic architecture of the ECCE test bench [4] is briefly presented. In this configuration the fuel cell system which acts as an energy source is coupled with a supercapacitor bank which acts not only as a power peak source but also as an energy recovery element, additionally batteries are used as a transient energy source and to regulate the DC bus voltage (Figure 2).

Figure 1. ECCE mobile test bench.

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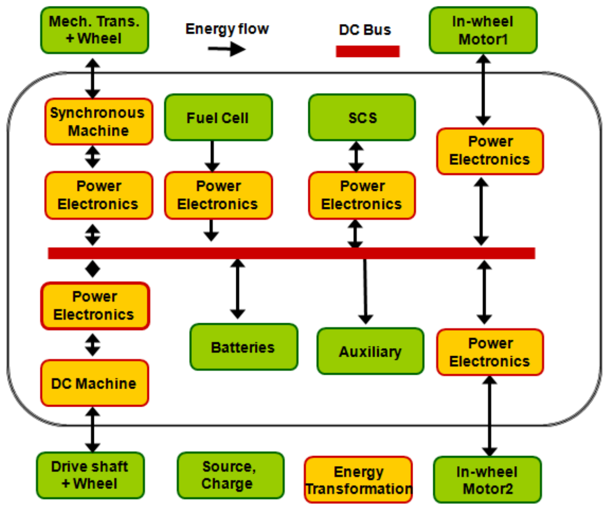


Figure 2. Energetic architecture of ECCE

A. *Generic EMR of the ECCE - DC Bus - Batteries*

The DC Bus is an electrical coupling element represented by a mono-physical coupling device and the batteries are represented with a source element. The batteries are connected directly to the DC bus and so they impose the DC bus voltage. Figure 3 shows the simplified EMR of the ECCE test bench. The model of the lead-acid batteries is based on that of Ceraolo [7] and its electrical schema is presented in Figure 4.

B. *EMR of the Fuel Cell Supercapacitors Systems bank*

In [4], a simplified EMR of the Fuel Cell System has been presented. This paper extends it by introducing the motocompressor group used to manage the air supply of the Fuel Cell stack. A rotary screw compressor coupled to a Permanent Magnet Synchronous Machine (PMSM) is used.

The EMRs and models of both PMSM and compressor group have been presented by Bouscayrol [5] and Boulon [6] respectively. Figure 5 presents the EMR of the motocompressor group including power electronics. In the ECCE test bench the energy required to supply the PMSM is provided by the DC bus.

To represent the supercapacitors, Lhomme [8] has presented not only the EMR but also the MCS of the supercapacitors system. The equivalent electrical circuit model presented by Zubieta [9] is shown in Figure 6.

C. *EMR of the ECCE test bench*

In the complete EMR of the vehicle, the pictograms representing the FCS the SCS and the MCG in the generic EMR (Figure 3) are replaced by their developed EMRs. The complete EMR of the selected energetic architecture of ECCE vehicle is shown in Figure 7.

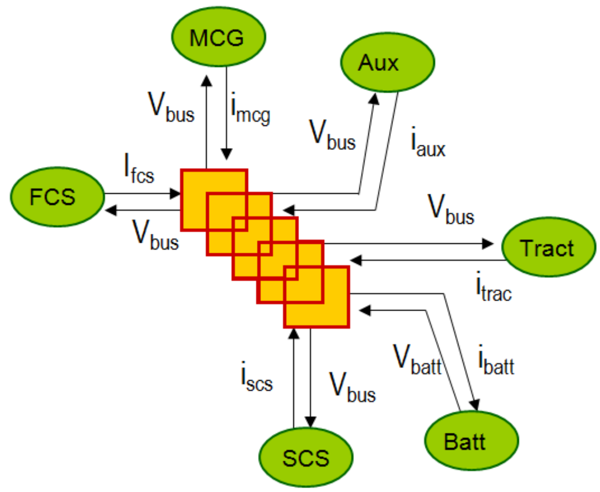


Figure 3. Simplified EMR of the ECCE Studied Architecture

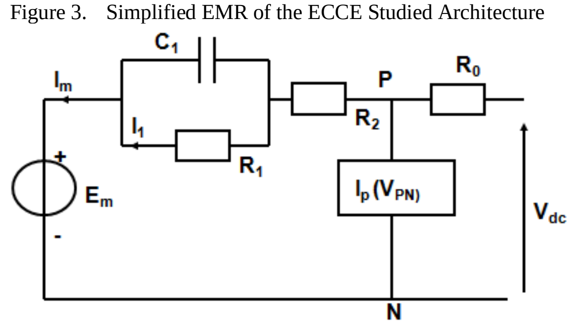


Figure 4. Ceraolo's Lead-Acid Batteries equivalent circuit model

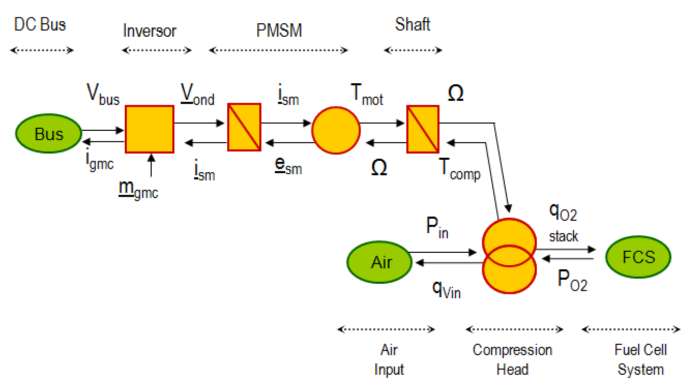


Figure 5. EMR of the motocompressor group

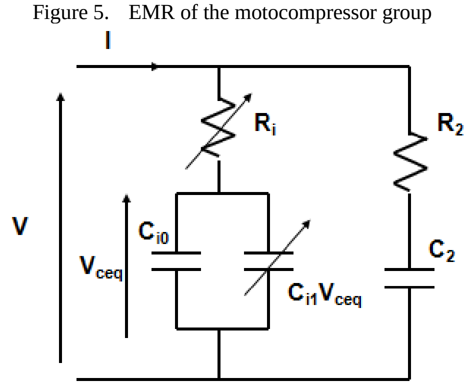


Figure 6. Zubietas' Supercapacitors equivalent circuit model

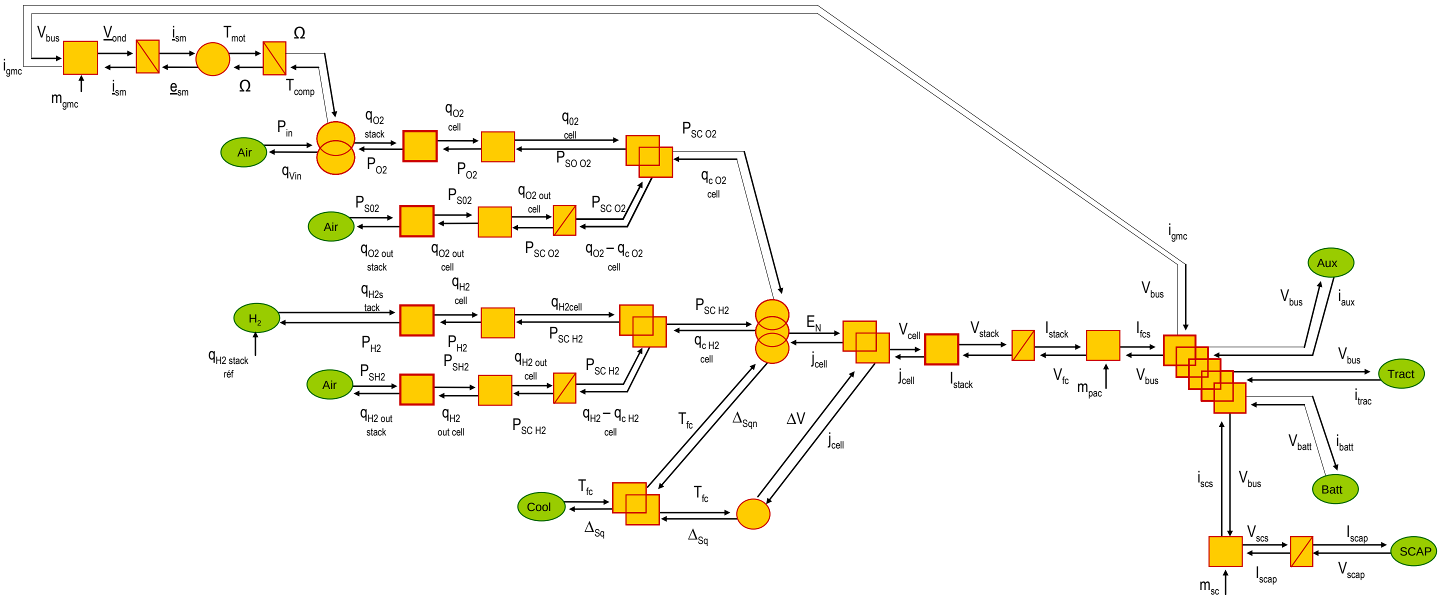


Figure 7. EMR of the ECCE test bench

III. Maximal Control Structure

The MCS considers all the theoretical calculations and measurements required by the EMR. Although these calculations are not always technically or financially feasible; this step is necessary to understand how to adapt the structure to achieve a practical, less expensive and perhaps a more realistic structure.

To deduce the MCS, the different control objectives have to be identified. Then the EMR blocks are inverted regardless of practical issues: the conversion blocks are directly inverted and the accumulation blocks are inverted using controllers in order to respect physical causality.

A. *MCS of the ECCE test bench*

The first two objectives are identified as the FCS and the SCS delivered powers. The batteries impose the DC voltage so the power of the FCS and the SCS is managed by controlling their currents. Additionally, the fuel cell stack voltage is defined as the third control objective. The stack voltage can be controlled with the air and hydrogen supply and the FCS and SCS power can be controlled with their respective power electronics.

The MCS of the PMSM, FCS and SCS have been presented respectively in [5,8,10]. To control the FCS power electronics, an equivalent control structure of those developed in the SCS is here considered. Figure 8 presents the global MCS of the whole ECCE test bench. The strategy unit represents the energy management strategy.

IV. Practical Control Structure (PCS)

The PCS is the final step in the EMR based methodology to find the control structure of a given system. It allows a technically and financially viable control system. The PCS could require modifications of the MCS using simplification hypotheses. This can obviously affect the quality of the control.

To go from the MCS to the PCS the measurements that are physically or financially infeasible are replaced and so have to be realised elsewhere. Then different strategies have to be proposed to compensate the loss of data.

A. *PCS of the ECCE test bench - Contraints*

Based on the MCS approach, the ECCE test bench will require 21 measurements for control purposes (Figure 8). Among these measurements there are four non physical measurements (Electromotive force (EMF), hydrogen and oxygen catalytic partial pressures and fuel cell overpotentials). Among the other seventeen, there are three relatively expensive (air and hydrogen output flows, and PMSM torque). We should look for a PCS using only the other twelve physical quantities.

B. *PCS of the ECCE test bench - MCS simplification*

The PCS of the ECCE test bench is a simplification of its MCS. The PCS for controlling the power levels in the FCS and SCS have no constraints and then their PCS are equivalent to their MCS without modifications. The MCS for controlling the fuel cell stack voltage is highly constrained and has to be simplified.

The simplification is made on the basis that the temporal delay of the gas in the supply channels is neglected. This hypothesis is justified because the time constants of the gas flow could be neglected regarding the (relatively slow-) energetic demand on the DC bus and also linked to the fact that the SCS guarantees the DC bus power fastest dynamics.

This simplification allows the number of theoretical sensors to be reduced to six, this is represented in Figure 9. A consequence of this simplification is that the gas flow references are fixed considering that there is not an associated delay.

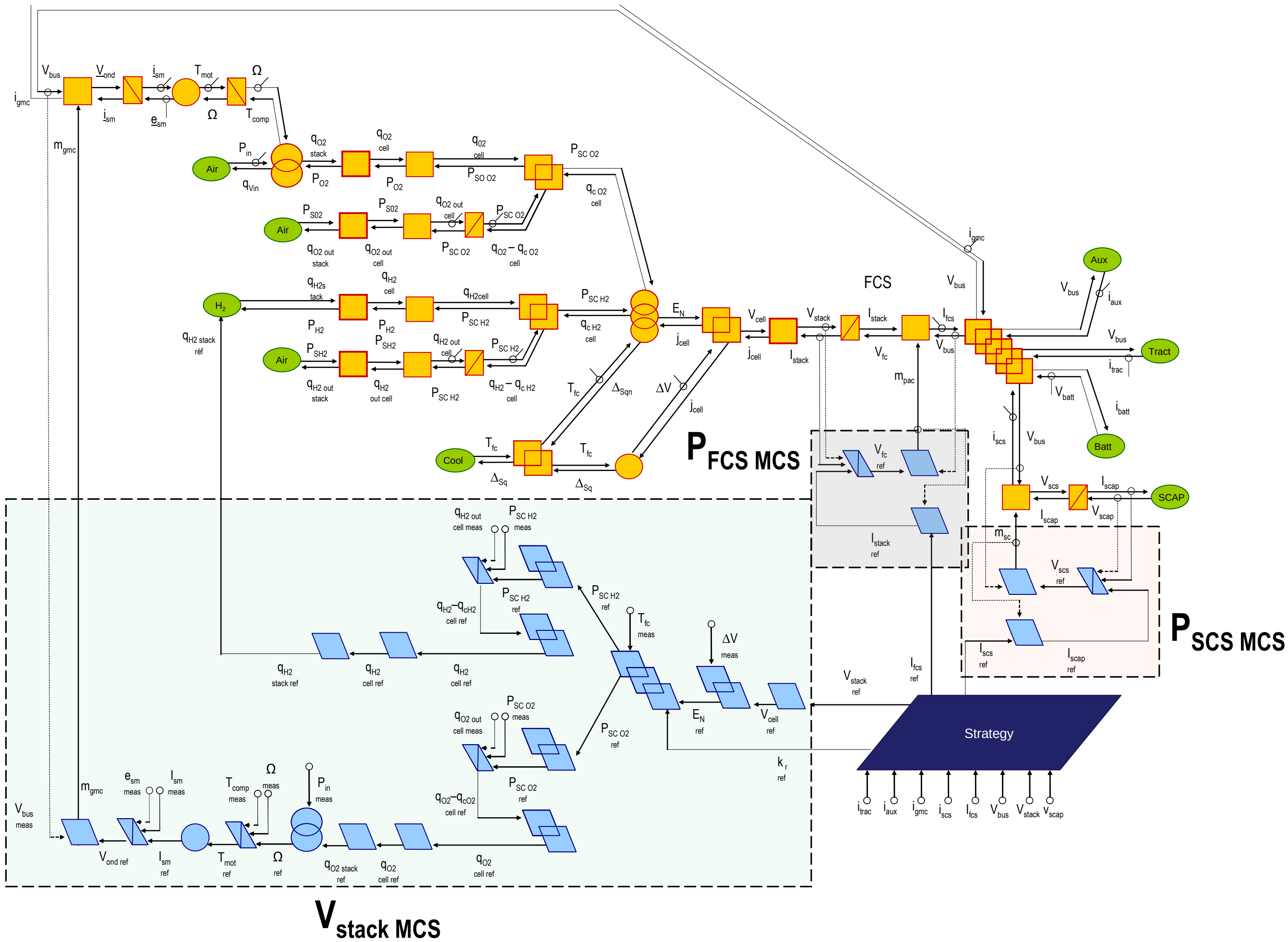


Figure 8. MCS of the ECCE test bench

C. *Estimated variables*

Among the non measurable physical quantities it is important to estimate those that permit inverting the control chain. The estimators in the open loop control are:

- Compressor torque. The compressor head torque is calculated from the rotor speed using mappings.
- PMSM EMF. This force is estimated using the PMSM current.
- Motocompressor input air pressure. The input pressure is considered as the standard atmospheric pressure.

D. *Motocompressor group PCS*

The PCS of the MCG can be developed from its MCS, considering the previous modifications. This is presented in Figures 10 and 11.

E. *PCS of the ECCE test bench*

To summarise the transformation from the MCS to the PCS, the first step was to identify the constraints, after that, simplifications were applied; finally the non-feasible measurements were estimated. Based on the MCS, the control of the ECCE test bench requires 21 measurements, based on the PCS it requires only 12 measurements. Six measurements were avoided using simplification hypotheses and three measurements are now estimated. Table 1 summarise all the different requested measurements at each control structure and Figure 12 presents the complete PCS.

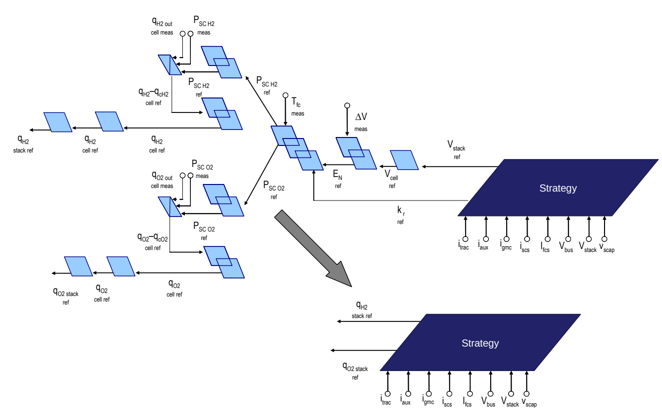


Figure 9. Simplification of the Voltage stack MCS

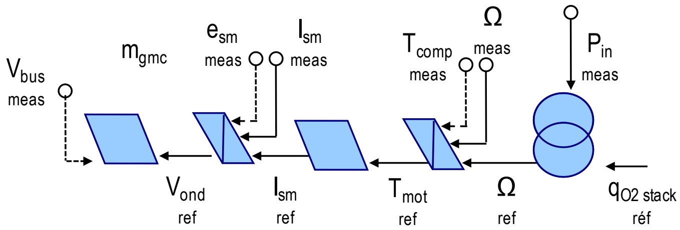


Figure 10. Motocompressor group MCS

Element - Physical quantity	MCS	PCS
Motocompressor - Speed	X	X
Motocompressor - Torque	X	
Fuel Cell stack - H_2 output flow	X	
Fuel Cell stack - O_2 output flow	X	
Fuel Cell stack - O_2 Catalytic Pressure	X	
Fuel Cell stack - H_2 Catalytic Pressure	X	
Motocompressor - Air input pressure	X	
Fuel Cell stack - Temperature	X	
Fuel Cell stack - Overpotentials	X	
PMSM - EMF	X	
DC Bus - Voltage	X	X
Fuel Cell stack - Output Voltage	X	X
Supercapacitors voltage	X	X
Ancillary current	X	X
Traction current	X	X
Supercapacitors Current	X	X
Fuel Cell stack - Output Current	X	X
Motocompressor group – DC current	X	X
Fuel Cell System - Output Current	X	X
Supercapacitors System Current	X	X
PMSM AC Current	X	X

Table 1. MCS and PCS required measurements

V. Application Example

To illustrate the PCS application, this paper presents some simulation results of the ECCE test bench. To simulate the complete multi physics system, a simple energy management strategy is considered.

The aim of the considered energy management strategy is to maintain the different source elements working within pre-established ranges. This strategy was used only for simulation purposes however in the ECCE test bench a different strategy will be implemented.

A. *Energy management*

In the ECCE test bench studied configuration, each component has a particular function. The FCS has to supply the mean energy of the traction system and provide for the lost energy dissipated in the different elements. The SCS has not only to boost the system but also has to recover a part of the braking energy.

The batteries act as a regulation element, they are connected directly to the DC bus then they will act as a transient energy source.

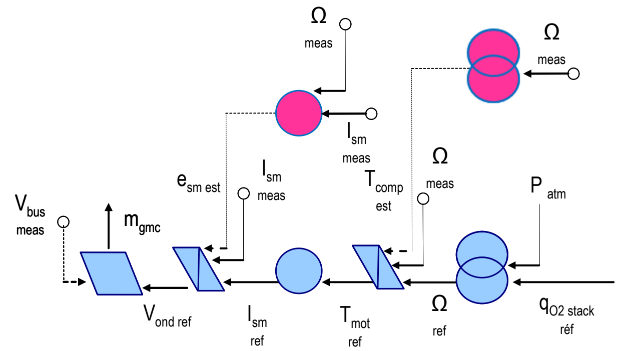


Figure 11. Motocompressor group PCS

Element	Operation ranges
FCS	$\frac{d\,P_{FCS}}{dt}\min < \frac{d\,P_{FCS}}{dt} < \frac{d\,P_{FCS}}{dt}\max$
	$P_{FCS}\min < P_{FCS} < P_{FCS}\max$
Batteries	$V_{batt}\min < V_{batt} < V_{batt}\max$
	$I_{batt}\min < I_{batt} < I_{batt}\max$
SCS	$\frac{V_{SCAP\ \ nom}}{2} < V_{SCAP} < V_{SCAP\ \ nom}$
	$I_{scs}\min < Iscs < I_{scs}\max$

Table 2. Operation Ranges of the energy and power sources

B. *Operational Ranges*

The use of real energy sources results in design limitations, it must be avoided to work outside the recommended operation limits. The FCS has dynamic constraints and also has upper and lower power bounds that have to be considered to extend its life.

The supercapacitors and batteries have upper and lower voltage and current limits, these are related to the amount of stored energy. Table 2 resumes the considered constraints for the different sources of the ECCE test bench.

C. *NEDC power profile simulation*

The objective of this simulation is to analyse the system response when a Normalized European Driving Cycle (NEDC) is used [4]. Figure 12 presents the simulation results. It is validated in simulation that the mean reference energy is supplied by the FCS, the mean energy balance in the SCS and the batteries tends to zero and the power peaks are supplied mostly by the SCS.

D. *Power step profile simulation*

The objective of this simulation is to analyse the system response in steady state and the step response. It can be verified in this case that the FCS supplies all the energy in steady state, the battery supplies the transient energy and finally the supercapacitors supply the fast dynamic power requirements. (Figure 13)

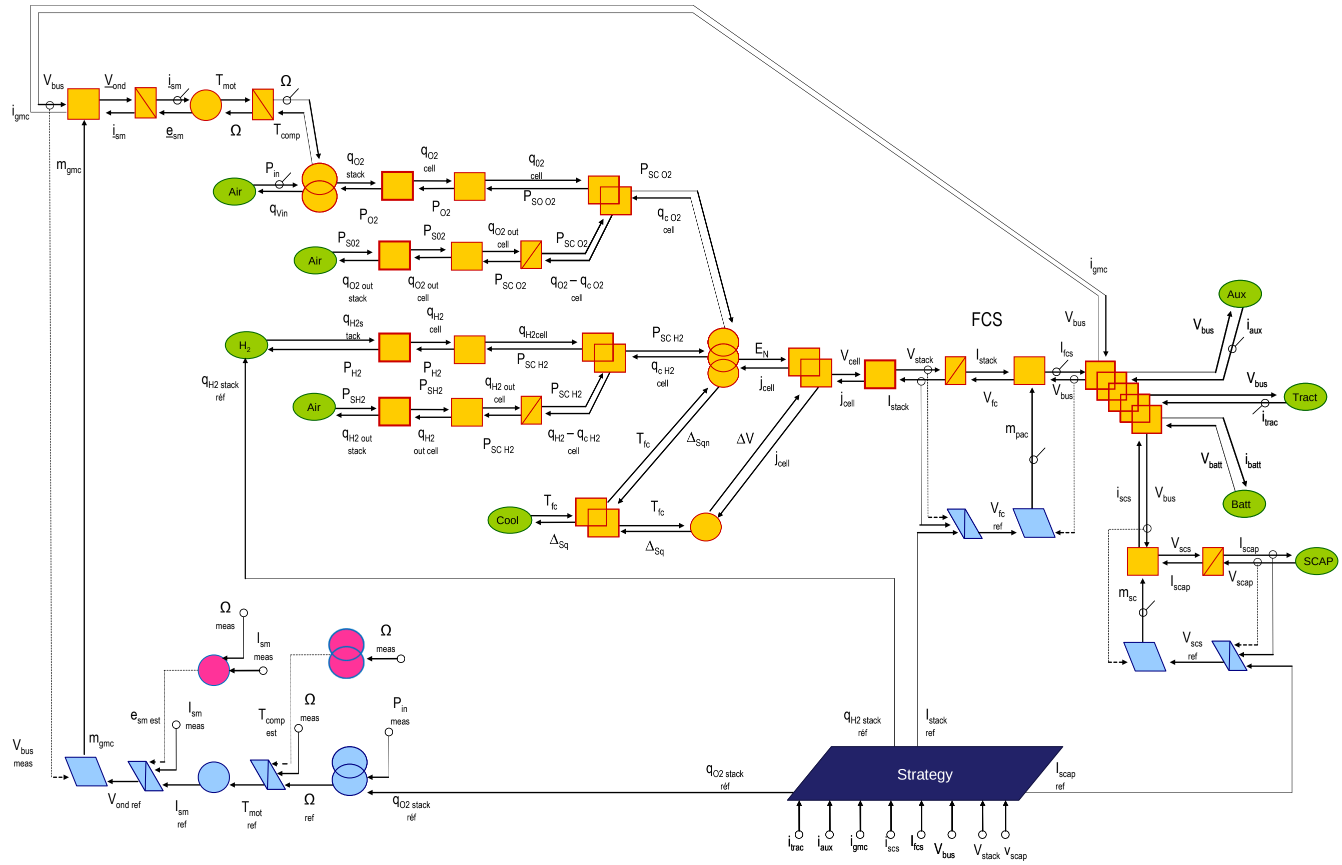


Figure 12. PCS of the ECCE test bench

VI. ECCE Energy Management Strategy

In this paper, a simple energy management strategy has been used. However, this strategy has to be improved to have better performances. A study about management strategies for electrical vehicles has been presented by Allègre [11].

In this vehicle, the relative high specific energy of the FCS is complemented with high specific power of the supercapacitors. The energy management is a complex problem. It is necessary to control not only the power flows, but also it is necessary to maintain the state of charge in SCS and batteries. The strategy block will allow controlling the power flows between the FCS, the SCS and the batteries. It is necessary to analyse the fact than the batteries are directly connected to the DC bus then the power is difficult to control.

Among the different control strategies, fuzzy logic has been successfully used to control hybrid electrical vehicles [2]. Nevertheless, classical fuzzy logic has problems to model uncertainty.

The ECCE test vehicle has several sources of uncertainty such as model simplifications, measurements or simulation. Mendel and John [12] have presented several works about type-2 fuzzy logic, this approach permits modeling the uncertainty which is not possible using classic type-1 fuzzy logic. Various works have shown that type-2 fuzzy logic controllers outperform their type-1 counterpart and have been already used in industrial applications such as speed control of diesel engines or power electronics applications [13].

VII. Conclusion

The MCS and the PCS of a hybrid electrical vehicle have been presented. This EMR based control approach permits identifying the control chains and identifying a real implementable control structure.

The next step of this work will focus on the energy management strategy. This strategy will be based on a type-2 fuzzy logic supervisor, this approach has several advantages with respect to the classic type-1 fuzzy logic approach, and it permits modeling the uncertainty.

References

[1] C. Espanet, J-M. Kauffmann and R. Bernard. “Comparison of two in-wheel permanent magnet motors for military applications,” IEEE Vehicle Power and Propulsion Conference 2006, 6 pages, Windsor, United Kingdom, 6-8 Sept. 2006.

[2] R. Pusca, Y. Ait-Amirat, A. Berthon, J-M. Kauffmann. “Fuzzy-logic-based control applied to a hybrid electric vehicle with four separate wheel drives”. Control Theory and Applications, IEEE Proceedings - , vol.151, no.1, pp. 73- 81, 17 Jan. 2004

[3] K. El Kadri, A. Berthon, “Energy Management Operating Modes Concerning a Hybrid Heavy Vehicle,” EUROCON 2007, The International Conference on "Computer as a Tool", On Page(s):1587 – 1593, Warsaw, Poland, Sept. 9-12, 2007

[4] J. Solano-Martínez, L. Boulon, D. Hissel, M-C. Péra and M. Amiet, “Energetic Macroscopic Representation of a Multiple Architecture

Heavy Duty Hybrid Vehicle". IEEE Vehicle Power and Propulsion Conference 2009, On page(s): 1322-1329, Dearborn, USA, 7-11 Sept. 2009.

[5] A. Bouscayrol, P. Delarue, and X. Guillaud. "Power strategies for maximum control structure of a wind energy conversion system with synchronous machine," Renewable Energy, Vol. 30, pp. 2273-2288, 2005.

[6] L. Boulon, M-C. Pera, P. Delarue, A. Bouscayrol and D. Hissel, "Causal fuel cell system model suitable for transportation simulation applications," ASME Journal of Fuel Cell Science and Technology, vol. 7, issue 1, 11 pages, Nov. 2009.

[7] M. Ceraolo, "New dynamical models of lead-acid batteries. IEEE transactions on power systems," IEEE Transactions on Power Systems, Volume 15, Issue 4, Page(s):1184 – 1190, Nov 2000

[8] W. Lhomme, R. Trigui, P. Delarue, B. Jeanneret, A. Bouscayrol, F. Badin. "Maximum control structure of a series hybrid vehicle using supercondensateurs," International Electric Vehicle Symposium, EVS21 2005, 12 pages, CD-ROM, Monaco April 2005

[9] L. Zubieta, R. Bonert. "Characterization of double-layer capacitors for power electronics applications." IEEE Transactions on industry applications, Volume 36, Issue 1, Page(s):199 – 205, Jan/Feb 2000

[10] L. Boulon, D. Hissel, A. Bouscayrol, M-C. Péra, P. Delarue. "Maximal and practical control structure of a PEM Fuel Cell System based on Energetic Macroscopic Representation." FDFC'2008 Fundamentals and Developments of Fuel Cells, CD-ROM, 11p., Nancy, France, 2008.

[11] Allegre, A.L.; Bouscayrol, A.; Trigui, R.; , "Influence of control strategies on battery/supercapacitor hybrid Energy Storage Systems for traction applications," Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE , vol., no., pp.213-220, 7-10, Detroit, USA, Sept. 2009

[12] J. M. Mendel and R. John, "Type-2 fuzzy sets made simple," IEEE Transactions on Fuzzy Systems, vol. 10, no. 2, pp. 117–127, Apr. 2002.

[13] H. Hagras, "Type-2 FLCs: A new generation of fuzzy controllers" IEEE Computational Intelligence Magazine, vol. 2, no. 1, pp. 30-43, Feb. 2007

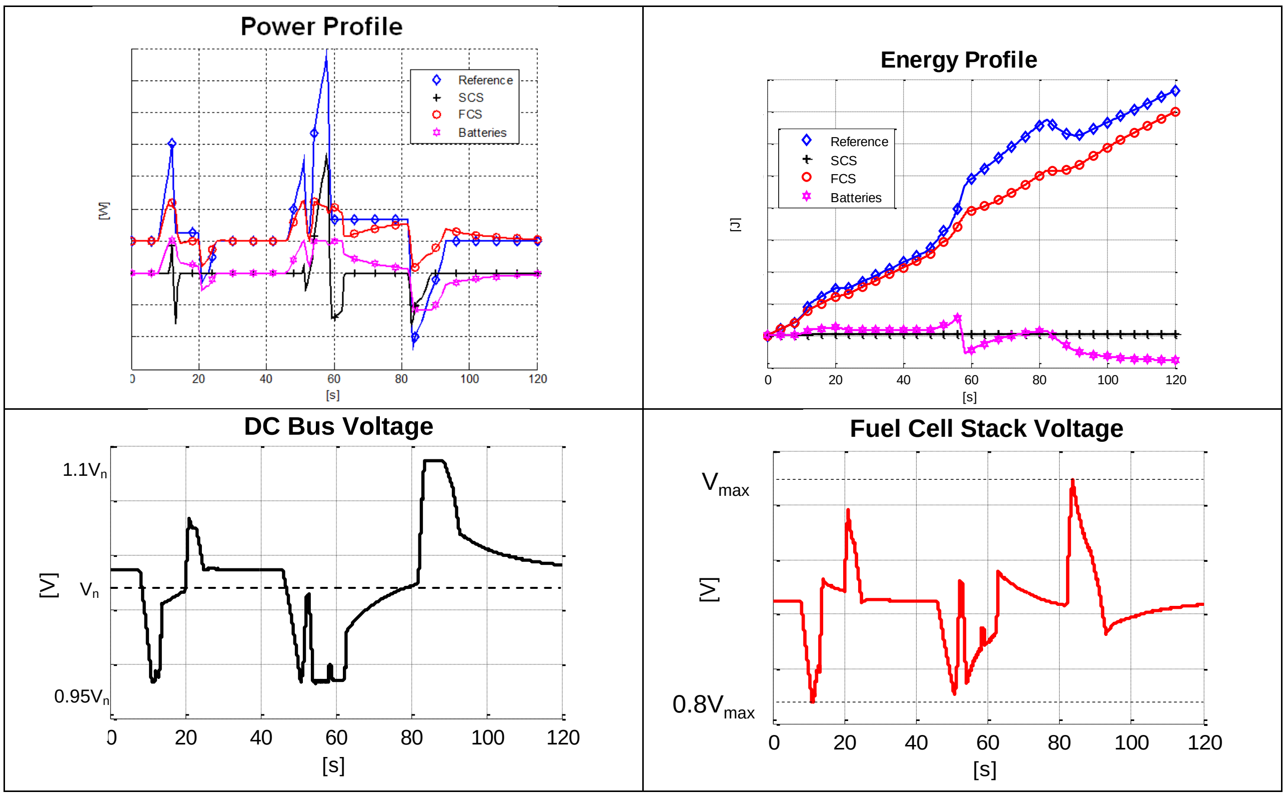


Figure 13. Simulation Results (Without axes information due to confidentially reasons)

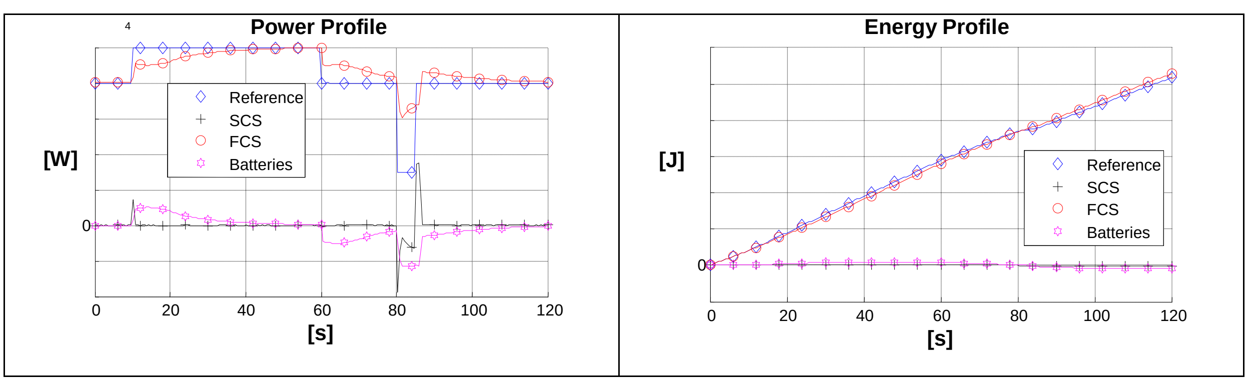
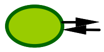
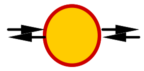
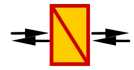
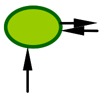
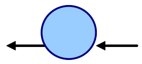
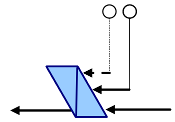
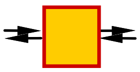
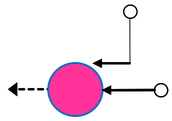
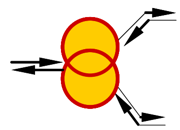
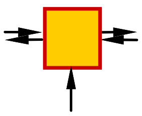
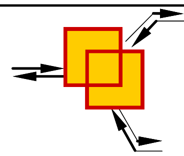
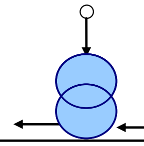
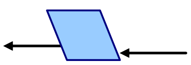
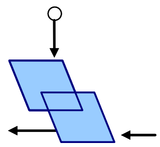
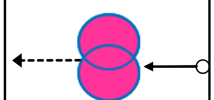


Figure 14. Simulation Results (Without axes information due to confidentially reasons)

Appendix A: Synoptic Of Energetic Macroscopic Representation

	Energy Source		Multi physical domain converter without energy accumulation		Energy accumulation element
	Adjustable energy source		Multi physical domain converter without energy accumulation inversion		Energy accumulation inversion (controller)
	Mono physical domain converter without energy accumulation		Multi physical domain converter without energy accumulation estimation		Multi physical domain coupling device (energy distribution)
	Adjustable mono physical domain converter without energy accumulation		Mono physical domain coupling device		Multi physical domain coupling device Inversion
	Mono physical domain converter without energy accumulation Inversion		Mono physical domain coupling device inversion		Multi physical domain coupling device Estimation