Modeling of an hybrid solar car with a lithium-ion battery

Laurianne Ménard, Stéphan Astier, Guillaume Fontès, Jean-Marc Blaquière, Christophe Turpin, Frédéric Gailly
Laboratoire Plasma et Conversion d'Énergie - CNRS (UMR 5213), INPT, UPS - FRANCE
laurianne.menard@laplace.enseeiht.fr

***Abstract*-"Sunracers", special solar cars using exclusively the electricity drawn from their embedded photovoltaic generator and designed to compete in solar races can be considered as special hybrid vehicles. This paper deals with the evolution of the serial hybrid architecture of the sunracer "Solelhada". This new architecture, decoupling the bus voltage from the battery state of charge by means of an inserted reversible chopper between the battery and the DC bus, is designed to improve the energy management. Simultaneously, a new design of the battery is proposed, based on lithium-ion technology and meeting vehicle constraints and several races requirements. With the aim of predicting the vehicle behavior with its new battery, an original Bond Graph model of the whole vehicle system is proposed. Based on Bond Graph modeling, it includes an advanced battery model which is detailed in the paper. A special bench has also been performed in order to emulate the whole vehicle behavior during different races, taking into account the new architecture.**

I. INTRODUCTION

Except geothermal or nuclear energy sources, the solar energy is at the origin of all other energy sources exploited by life and mankind; so it has a symbolic character with the aim of "sustainable development". Even if modern transport systems are synonymous of liberty, they are also responsible for greenhouse effect. As a consequence, solar vehicles called "sunracers" which can cross the Australian continent [1] at average speeds up to 100 km/h, using exclusively the electric energy drawn from their embedded photovoltaic (PV) generator, are symbolic of the dream of conciliating our moving needs with ecology. Nevertheless, such a challenge is only achieved with very high performance vehicles, specially optimized in terms of energy saving. Such systems are very representative of many other ones dealing with the general problem of the optimal design of high efficiency autonomous systems. Beside an intrinsic great interest for searchers and students, this is a reason why such a sunracer have been designed and studied in our university: it is called Solelhada.

For a decade, Solelhada competed for several races. Indeed, it successfully competed in the "2001 Solar Odyssey" crossing the Australia on 3010 km at an average speed of 60 km/h, only using 47 kWh exclusively drawn from its PV generator, the equivalent of only 6 l of fuel (Fig. 1). Solelhada also competed since 2000 for several "Rallyes Phébus" between Spain and France and recently won the first Solar Event in Chambéry (France) in 2008, proving its reliability and its sobriety for energy saving. Indeed, consuming only a 1000 W electric power to run at 60 km/h on a windless flat road, its characteristic consumption is established to 20 Wh by kilometer, i.e. ten times less compared to a classical car. Such performance requires a very special car with very light mass and very low aerodynamic drag and friction coefficients and also very efficient energy management. For now, the solar energy has been stored on board in a lead-acid battery directly connected to a main DC bus. But in the past few years, lithium-ion (li-ion) batteries have become much more interesting than any other kind of batteries in terms of energy-to-weight ratio, energy-to-volume ratio and voltage level. This is the reason why a new electric architecture involving a new li-ion battery is studied, for improved energy management and performance.

Fig. 1. Solelhada crossing Australia during 2001 Solar Odyssey.

The aim of this paper is to present this study with the battery design and modeling. It is shown first that the particular architecture of Solelhada can be considered as a serial hybrid one. A general comparison with parallel hybrid architecture is given. In order to predict Solelhada behavior in a race, an original model of the whole vehicle is presented. Based on Bond Graph modeling, it involves the models of the vehicle dynamics, the permanent magnet DC Brushless wheel motor, the embedded solar array and the battery. Then, the design of the new li-ion battery to be connected in a new electric architecture for a better energy management and taking into account several races requirements is presented. The battery model is particularly detailed. This new architecture involves a reversible chopper between the battery and the DC bus. To validate this new configuration, a special experimental bench able to emulate the electric architecture has been performed. Both experimental and simulation results can lead to a better understanding and analysis of the vehicle behavior and energy management.

II. SOLELHADA: A PARTICULAR SERIAL HYBRID SOLAR VEHICLE

Hybrid vehicles classically involve both an Internal Combustion Engine (ICE) and an Electric Motor and/or a Generator (SC-EM/ G) associated to Static Converters (SC) used to manage energy flows. They are interconnected by means of a very great variety of possible architectures: hybrid

978-1-4244-8218-4/10/$26.00 ©2010 IEEE

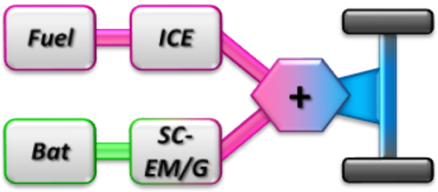

Fig. 2. Typical parallel hybrid architecture.

parallel or serial or power derivation mixing serial and parallel as in the Toyota Prius.

Typical parallel hybrid architecture is shown in Fig. 2. It can be defined by a summation of ICE and SC-EM/G powers in the mechanical domain by means of a mechanical junction. This architecture enables both the downsizing of ICE and EM/G, which is fine for cost, but the operation speed of the ICE remains dependant of the vehicle one, which penalizes the consumption and CO2 emissions reduction.

Typical serial hybrid architecture is shown in Fig. 3. It can be defined by a summation of ICE/SC-EG and battery (BAT) powers in the electrical domain by means of an electrical junction. In this architecture all the driving power passes through the electric motor EM/G and the associated inverter, therefore full power sized, which is a drawback for cost, but the operation speed on ICE can be totally independent from the vehicle speed. It can be also considered as a pure electric vehicle embedding an electric generator used as a range extender charger. Thence, in a more general way, every electric vehicle involving embedded electric generator with such an hybridized architecture can be considered as serial hybrid. An example is given with fuel cell vehicles involving a battery or supercapacitors. This hybridization enables the independence of the electric generator operation from the vehicle speed and power reversibility for regenerative braking.

Another example is given with most of sunracers in which the hybridization is necessary for MPPT operation of the embedded PV generator, regenerative braking and, first of all, a running ability independent from sun power for security. Solelhada architecture given in Fig. 4 clearly appears like a serial hybrid one.

III. THE WHOLE SOLAR VEHICLE MODEL

A. *Presentation of the vehicle model*

An original energy approach has been chosen to model the solar vehicle. It is applied via Bond Graph formalism, an explicit graphical and multi-physical tool for describing energy exchanges within a system [2]. The solar vehicle is made of heterogeneous parts exchanging energy and power: mechanical part, solar PV generator, inverter, brushless wheel-motor.

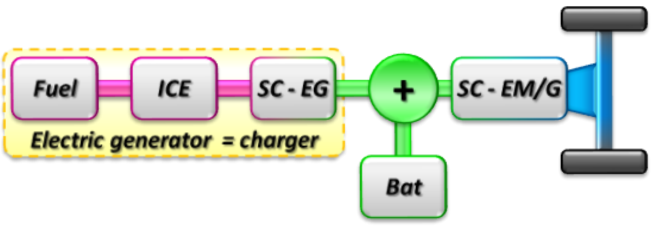

Fig. 3. Typical serial hybrid architecture.

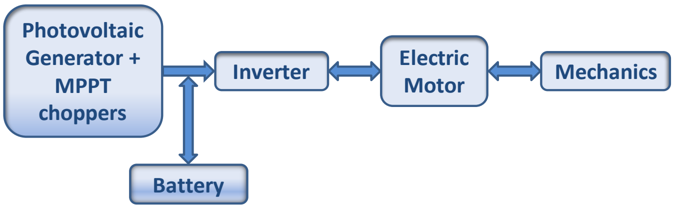

Fig. 4. 1st configuration: the battery is directly connected to the DC bus.

Referring to the electric architecture in Fig. 4, the energy model structure is given in Fig. 5, with a 0 junction connecting together the photovoltaic generator model with the storage device model and the brushless motor driving the vehicle dynamics model. To have a more synthetic view, models of each part is not detailed in this paper. Only the model of the lithium-ion battery has been improved since [3] and is detailed below.

B. *Experimental validation of the vehicle model*

To validate the vehicle model presented above, measurements on the vehicle during a “Solar Event” race have been exploited. Thanks to a data acquisition system embedded in the vehicle, battery current, battery voltage, input current of the inverter, motor current, or power density of solar radiation are recorded every 0.5 seconds. It has to be noted that the vehicle is in the 1st configuration during the measurement (Fig. 4); the lead-acid battery is directly connected to the DC bus, as modeled in Bond Graph.

The Bond Graph vehicle model can be simulated with 20Sim software. Input data are road profile (hypothesis of a flat road is made), power density of solar radiation and input current of the inverter (as the current reference for the inverter). Bond Graph modeling enables access to many data, in the electrical, chemical or mechanical field. Some of them, like the inverter input current, the battery current and voltage, can be compared to the ones measured in the vehicle to conclude on the efficiency of the Bond Graph model.

Modeled and measured inverter input currents are presented in Fig. 6. The Bond Graph model reproduces well the global behavior of the inverter regulated input current. Nevertheless, a maximum error occurs at high current pulses, the regulation modeled at the input of the inverter does not seem fast enough. Moreover, it seems difficult to perfectly model the load that represents the vehicle and its interactions with the environment (aerodynamics, friction).

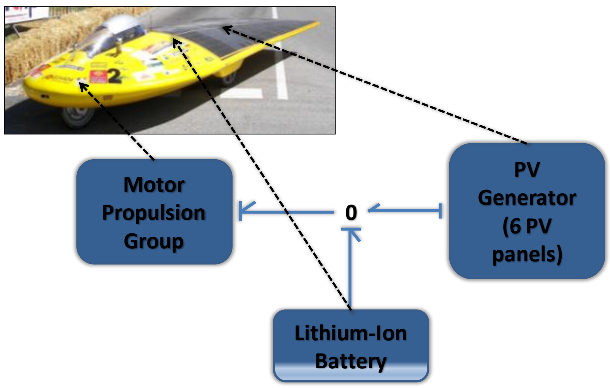

Fig. 5. Solelhada Bond Graph model.

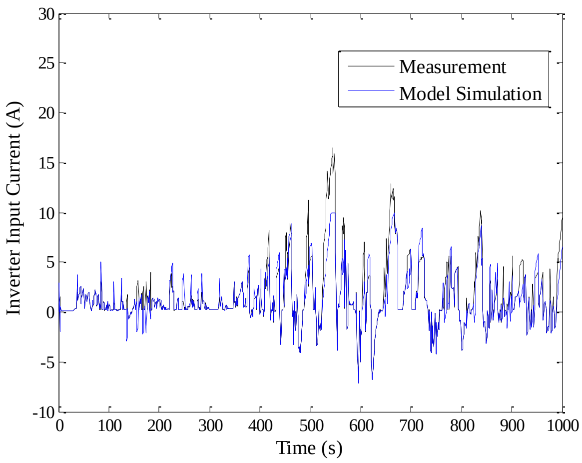

Fig. 6. Measured and modeled inverter input currents.

Battery currents of the model and the vehicle acquisition are presented in Fig. 7. The problem of the inverter input current at high current pulses is reflected in the battery current. Nevertheless, the model has a good behavior in the case of the battery charge. During the first 300 seconds, solar radiation power density was effective but the battery is not charged because the PV generator was manually disconnected and there was no regenerative braking. PV generator was connected at the end of the 300 seconds.

To evaluate the behavior of the storage part model, modeled and measured battery voltages are presented in Fig. 8. The maximum error is a 6 V voltage gap between the model simulation and the measurement. In view of the DC bus mean voltage level (150 V), this gap represents nearly a 4 % error, which is acceptable. Results shown in Fig. 8 prove that the DC bus depends on the state of charge of the battery. Indeed in the 1st configuration, the battery voltage is the DC bus voltage, which makes this latter fluctuate according to the current profile.

This configuration can be problematic in the case of a sunny weather, when the battery is nearly completely discharged and the driver wants to drive fast or begin a rise. The DC bus voltage will be too low to supply enough power to the motor propulsion group. That is the reason why a new architecture implementing a chopper between the battery and

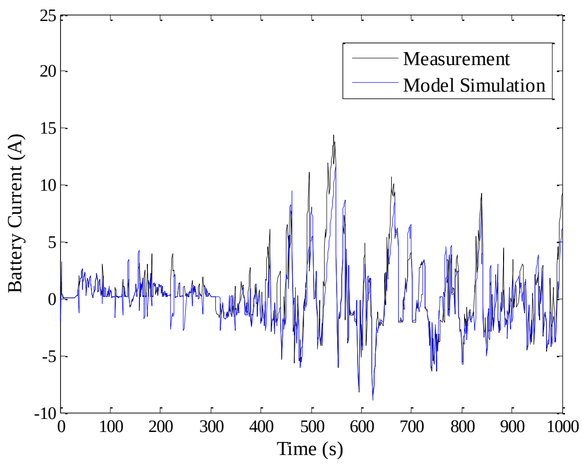

Fig. 7. Measured and modeled battery currents.

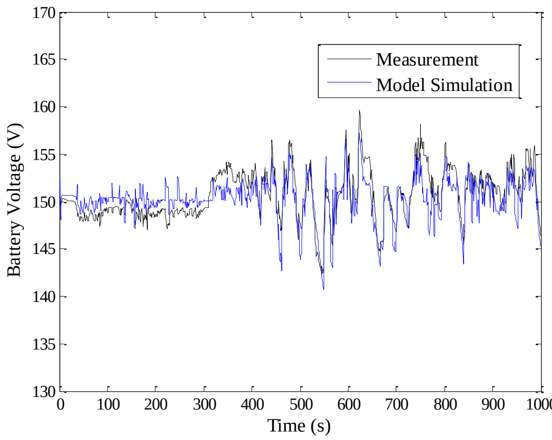

Fig. 8. Measured and modeled battery voltages.

the bus to have a constant DC bus voltage has been studied both with the design of a new li-ion battery.

IV. New Architecture and Reconfigurable Lithium-Ion Battery Design

Simultaneously with the design of a new electric architecture for a better energy management, in order to both improve the sunless autonomy and reduce the embedded mass, it has been planned to replace the lead-acid battery by a li-ion battery, while keeping the main other components of this high-performance vehicle: brushless motor and inverter, PV generator and associated MPP trackers. That results in specific requirements and constraints.

A. Reconfigurable lithium-ion battery

1. Vehicle constraints

Two configurations are considered for the implementation of a li-ion battery in the serial hybrid architecture. The 1st configuration is the current vehicle configuration presented in Fig. 4, a classical direct battery connection on the DC bus. The 2nd configuration is the new vehicle architecture, studied to improve energy management and vehicle efficiency. The battery is connected on the DC bus through a chopper, as shown in Fig. 9. The DC bus becomes independent of the state of charge of the battery which can be interesting as explained previously.

As it will be used in both configurations, the battery has to be reconfigurable from the 1st to the 2nd configuration and vice versa, it has thus to be composed of modules. Moreover, the battery is located in a ventilated trunk and the maximum charge and discharge currents can be separately controlled.

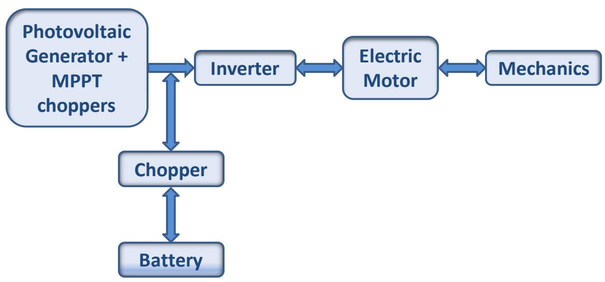

Fig. 9. 2nd configuration: the battery is connected on the DC bus via a reversible chopper.

For Solelhada application, the maximum discharge current is 40 A and the maximum charge current is 25 A.

2. Races requirements

Each race has its own requirements. Most of the time, requirements are based on PV surface and more particularly on the battery embedded energy, that is to say the battery embedded mass. On the one hand, the Solar Event taking place in Chambéry requires only 3 kWh embedded energy, or a 21 kg battery embedded mass since the weight energy of a li-ion cell is considered equal to 140 Wh/kg. On the other hand, the World Solar Challenge taking place in Australia allows 5 kWh embedded energy. The goal here is to design a reconfigurable battery that could meet these two race requirements.

3. Design of the reconfigurable lithium-ion battery

In this study, two li-ion technologies are focused on, lithium iron phosphate ($LiFePO_4$) and lithium cobalt oxide ($LiCoO_2$) positive electrodes. $LiFePO_4$ technology is more stable, then safer than $LiCoO_2$, it is also cheaper. Nevertheless, $LiCoO_2$ technology offers higher voltage and capacity. Battery design was achieved thanks to an automatic algorithm that determines the best cell reference to build the best battery configuration, meeting voltage, energy, and current levels requirements.

The li-ion battery design based on $LiCoO_2$ cathodes is schematized in Fig. 10. The battery pack is composed of 6 modules. These modules can be placed either in the 1st or in the 2nd configuration. Each module is composed of 14 MP174565 Integration li-ion cells manufactured by SAFT, put in series. As a cell has a 3.75 V nominal voltage, a module has a 52.5 V nominal voltage and the 1st and 2nd configurations reach respectively 157.5 V and 105 V nominal voltages. Moreover, as a cell has a 4.8 Ah capacity, the energy of a module is 252 Wh, which leads to a 1.5 kWh battery pack either in the 1st or the 2nd configuration. At least, two 1.5 kWh battery packs can be put in parallel to form the 3 kWh battery required for the "Rallye Phébus". Putting three battery packs in parallel meet the requirements of the World Solar challenge, with 4.5 kWh embedded energy. In terms of current limits, the maximum continuous discharge current of a 3 kWh battery is 38.4 A which is close to the vehicle constraint. The maximum continuous charge current of a 3 kWh battery is 19.2 A, which is lower than the current regenerative braking current (25 A). Nevertheless, this current limit can be controlled directly in the vehicle.

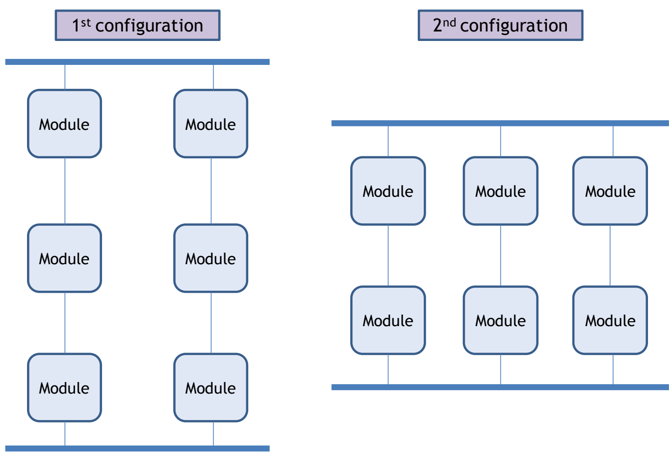

Fig. 10. Structure of a battery pack for two different configurations (cf. Fig. 4 and Fig. 9).

The li-ion battery design based on $LiFePO_4$ cathodes is also schematized in Fig. 10. The structure is exactly the same as for $LiCoO_2$ cathodes, only the modules differ. Each module is composed of 16 AHR32113 Gen2 li-ion cells manufactured by A123, put in series. A cell has a 3.3 V nominal voltage, which is lower than $LiCoO_2$ technology. Putting 16 of them in series leads to nearly the same nominal voltage level for a module and for a battery pack as with the LiCoO2 technology. As said before, $LiFePO_4$ technology offers lower capacity than $LiCoO_2$. In this case a cell has a 3.6 Ah capacity, which leads to a 190 Wh module and a 1.2 kWh battery pack either in the 1st or the 2nd configuration. At least, two battery packs can be put in parallel for the "Rallye Phébus", but the embedded energy will be lower than 3 kWh (2.4 kWh). Nevertheless, putting four battery packs in parallel meet the requirements of the World Solar challenge, with 4.8 kWh embedded energy. Charge and discharge current limits are larger than $LiCoO_2$ ones.

B. Model of the new lithium-ion battery

To adapt the vehicle Bond Graph model [3], a new lithium-ion battery model is described and validated. Its structure is shown in Fig. 11. Since [4], modeling of the diffusion phenomenon has been improved.

1. Description of the lithium-ion battery model

1) Storage and energy conversion: the ideal instantaneous energy conversion (power conversion) from the electrochemical field to the electrical one can be modeled by expressing the conservations of both energies, matter and electrical charge, which leads to (1) and (2) relations.

$$E = -\Delta G / nF, \tag{1}$$

$$I = nFJ, \tag{2}$$

where E is the battery electromotive force or open-circuit voltage (OCV), ΔG is the free enthalpy variation of the

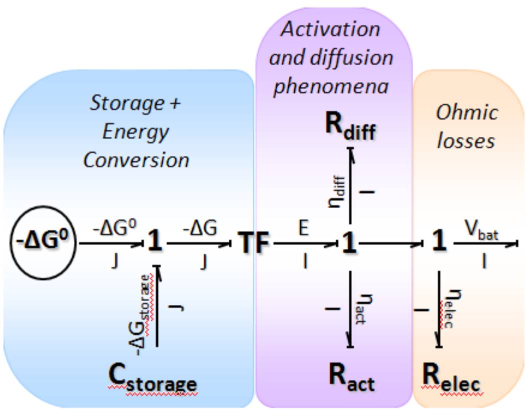

Fig. 11. Bond Graph model of the li-ion battery.

electrochemical reaction, I is the current of the battery, J is the molar flow of li ions, F is the Faraday constant and n is the number of li ions moles exchanged for one mole of electrons [5]. The transition between the chemical and the electrical fields can be modeled by a TF element in Bond Graph formalism, as shown in Fig. 11. The transformer ratio is nF.

In a battery the chemical potential, i.e. the free enthalpy variation ΔG, partially depends on the energy stored in the battery, i.e. on the li storage in the electrodes. As shown in (3), ΔG can be expressed as the sum of two terms, a reference free enthalpy variation ΔG^0 and an available amount of chemical stored free energy $\Delta G_{storage}$.

$$\Delta G = \Delta G^0 + \Delta G_{storage}. \quad (3)$$

In Bond Graph formalism, as the matter flow is common, imposed by the molar flow J, this sum can be modeled by a 1-junction. As $\Delta G_{storage}$ is linked to lithium storage, a Bond Graph storage element C, called $C_{storage}$, has been used to model it.

2) Activation and diffusion phenomena: activation phenomenon is associated to the kinetic of the electrochemical reaction, taking place at the electrode-electrolyte interface. As a dissipative phenomenon, it causes a voltage drop η_{act} linked to the electron transfer current I by (4).

$$R_{act} = \eta_{act} / I, \quad (4)$$

The activation phenomenon can thus be modeled by a dissipative element R_{act} connected through a 1-junction to give the voltage drop η_{act}. Insertion materials used in li-ion batteries are porous electrodes into which lithium ions diffuse, which causes energy dissipation. During a battery discharge, diffusion phenomena generate a voltage drop η_{diff} towards the OCV and linked to the electron transfer current I, as in (5).

$$R_{diff} = \eta_{diff} / I, \quad (5)$$

The losses are thus modeled by a dissipative element R, named R_{diff}. It has to be noted that R_{act} and R_{diff} depend on the battery OCV.

3) Ohmic losses: they are related to the electric conduction phenomenon, particularly taking place in all conductors and interfacial contacts of the battery. The resistance of the electrolyte seems higher than all the other ones [6]. This phenomenon causes a voltage drop η_{elec} in the case of a battery discharge, proportionate to the current. In Bond Graph, losses are modeled by a dissipative element R, here called R_{elec} connected through a 1-junction in order to cause a voltage drop.

2. *Model validation on a $LiCoO_2$ lithium-ion cell*

To validate the li-ion battery model presented above, successive discharges of a li-ion cell have been exploited. The battery is subjected to current square waveforms and its voltage is measured for two different current amplitudes: C/3 in Fig. 12 and C/2 in Fig. 13, C being the total capacity of the considered li-ion battery. With the same parameters values, the model stays effective for both amplitudes, with a maximum 20 mV error.

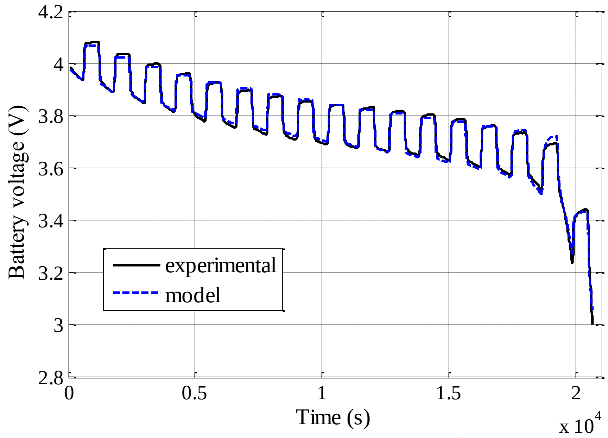

Fig. 12. Experimental and model battery voltages for a C/3 current waveforms amplitude.

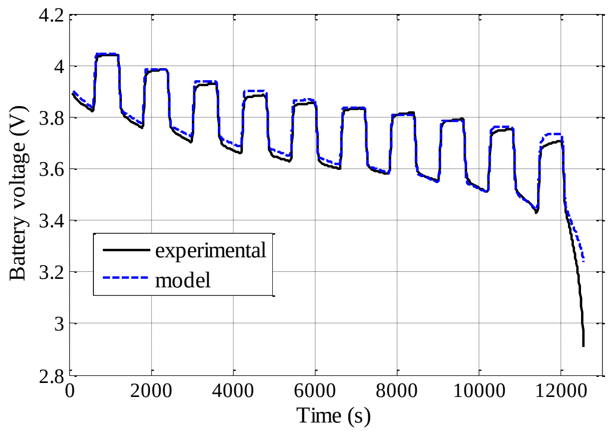

Fig. 13. Experimental and model battery voltages for a C/2 current waveforms amplitude.

C. *Experimental validation of the new vehicle architecture*

With a new reconfigurable and modeled li-ion battery, the goal is to experimentally test its indirect connection on the DC bus, through a chopper (Fig. 9). An emulation bench has been built to run this test.

1. *Presentation of the emulation bench*

The PV generator and its MPPT choppers are emulated by a power supply and the motor propulsion group by an active load. These two parts are controlled by a Dspace interface that sets the PV current profile, the load current profile, recorded during a “Solar Event” race, and the DC bus voltage. The Dspace interface also retrieves electrical data at the input and the output of the chopper.

The power supply, the battery and the reversible chopper as a whole, and the active load are connected through an electrical closet which behaves like a Kirchhoff node. Indeed, electrical devices connected to this node that can be sources or loads are actually linked to a bus and thus have the same electric potential. As a consequence, powers and currents have to be controlled while voltage is settled by one of the sources.

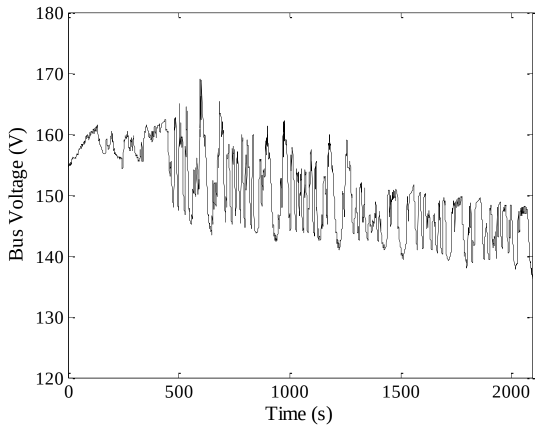

Fig. 14. DC bus voltage measured in the vehicle, in the case of a direct connection between the battery and the bus.

2. A DC bus voltage independent of the state of charge of the battery

In Fig. 14, DC bus voltage is represented for the 1st configuration (Fig. 4). As the battery is directly connected to the bus, DC bus voltage is also battery's one. This voltage was measured during another "Solar Event" race, where the vehicle average speed was higher. DC bus voltage obviously fluctuates, leading to not enough power to accelerate at the end of the race.

Thanks to the emulation bench previously described, the same race profile is focused on, with now a reversible chopper between the battery and the DC bus (Fig. 9). DC bus voltage can be measured (Fig. 15) in this new architecture. This result proves here that the reversible chopper can be reliable during a 30 minutes race and insure the stability of the voltage independently from the battery state of charge.

At this step, more simulations and tests have to be made with the actual new battery (not yet available) before implementing the chopper and battery in the vehicle, but results presented here stay encouraging.

V. CONCLUSION

The sunracer Solelhada has proven its sobriety and efficiency competing in several races with a classical serial hybrid electric architecture. In order to improve the energy management, a new architecture has been designed.

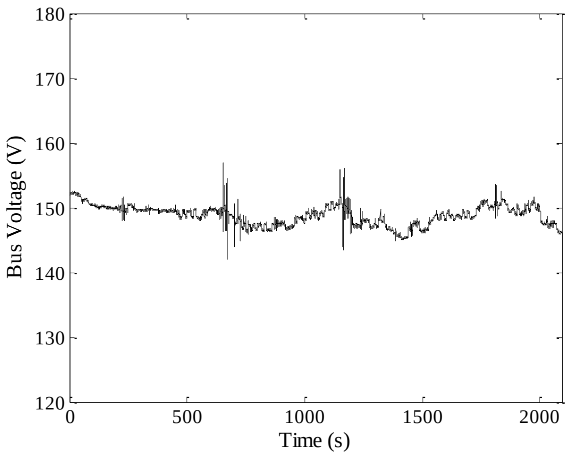

Fig. 15. DC bus voltage measured on the emulation bench, in the case of a reversible chopper connection between the battery and the bus.

It enables to obtain a DC bus voltage independent from the battery state of charge by means of inserting a well designed DC-DC reversible chopper between the battery and the bus. This will enable a better adaptation of the DC bus voltage to the race conditions.

Simultaneously, so as to reduce the embedded mass a new li-ion battery has been designed. Two li-ion batteries meet the different races requirements; their modularity enables to switch from a direct connection of the battery on the DC bus to the new indirect one, through a reversible chopper. Now, the final choice has to be made between $LiFePO_4$ technology which is safer and $LiCoO_2$ technology which provides higher voltage level and capacity, then fewer cells. A li-ion battery model has thus been developed and validated to be integrated to the whole Bond Graph vehicle model. Bond Graph formalism has been chosen to model the vehicle and predict its behavior. As a multi-disciplinary language in terms of power and energy exchanges, this modeling tool is well adapted for a system involving electrical, mechanical and chemical fields. Nevertheless, results show that modeling of the load and the inverter current regulation still has to be improved.

Finally, an emulation bench has enabled the study of the new architecture, with a reversible DC-DC chopper connection between the battery and the DC bus. First measurements on the bench show that the DC bus is nearly constant for a 30 minutes on a realistic race profile. Nevertheless, longer tests are needed to evaluate the reliability of the reversible chopper and test the actual new battery when available.

REFERENCES

[1] http://www.wsc.org.au/

[2] D.C. Karnopp, D.L. Margolis, and R.C. Rosenberg, *Systems Dynamics: Modeling and Simulation of Mechatronics Systems*, 3rd ed., John Wiley and Sons, 2000.

[3] S. Astier, R. Saïsset, and X. Roboam, "Modelling and study of a solar car with embedded photovoltaic array and Li-ion storage," presented at the Int. Conf. Integrated Modeling & Analysis in Applied Control & Automation, Genoa, Italy, Oct. 28-30, 2004.

[4] L. Ménard, G. Fontes, and S. Astier, "Dynamic Energy Model of a Lithium-Ion Battery," presented at the Int. Conf. ELECTRIMACS, Québec, Canada, Jun. 8-11, 2008.

[5] M.D. Levi, C. Wang, D. Aurbach, and Z. Chvoj, "Effect of temperature on the kinetics and thermodynamics of electrochemical insertion of li-ions into a graphite electrode," *Journal of Electroanalytical Chemistry*, vol. 562, pp. 187-203, Feb. 2004.

[6] R.C. Kroeze and P.T. Krein, "Electrical battery model for use in dynamic electric vehicle simulations," in *Proc. IEEE Power Electronics Specialists Conference*, 2008, pp.1336-1342.