Power Hardware-In-the-Loop test of low-voltage battery for a plug-in hybrid electric vehicle

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Battery testing, electric vehicle, hardware-in-the-loop, energetic macroscopic representation.

Abstract
A methodology developed for a quicker validation of various sub-systems is applied in this paper. It is based on two steps, i.e. the simulation validation and the power Hardware-in-the-Loop (HiL) testing. A new plug-in hybrid electric vehicle with low-voltage battery has been validated on a demo car. A new battery with higher power density is proposed to minimize the energy losses. Before its integration in car, simulation and hardware-in-the-loop tests are achieved. For the HiL part, a real-time simulation of the powertrain is coupled to the battery to test various driving conditions. A dedicated emulation interface is developed. The tests in this paper demonstrate the ability of the battery to operate in a safe condition for the vehicle using a WLTC driving cycle.

Introduction
The development of electrified vehicles is a on the road to reduce the greenhouse gases of the transport sector [1]-[3]. The European Commission is managing several research projects to speed up the development of battery electric vehicles, hybrid electric vehicles and fuel cell vehicles [4]-[6]. As example, the H2020 PANDA European project [7] deals with a unified modelling method for virtual and real testing of electrified vehicles and their components. In that aim, the Energetic Macroscopic Representation (EMR) formalism [8] is used to organize the simulation models of these electrified vehicles, for different development tasks. Siemens has integrated an EMR library in its well-known Simcenter AMESIM simulation package [9]. Multi-level models have thus been developed for batteries and electric drives of different electrified vehicles in a cloud to be used for virtual tests of new components but also for real tests (i.e. hardware-in-the-loop testing).
Low-voltage batteries are developed in hybrid electric vehicles to avoid a too high DC bus and associated safety constraints [10][11]. Valeo is developing a low-voltage hybrid powertrain that has already been implemented in a demo-car [12]. A gasoline car has been thus retrofitted using a 48V battery. This plug-in hybrid electric vehicle has also been simulated using the PANDA method and the actual battery leads to a small gain in terms of energy consumption [12]. A new battery with a higher power density is now considered to increase the energy saving. Indeed, high power batteries are designed to have low series resistance. As a consequence, the joule losses are minimized. The new battery must be tested before its implementation in the demo-car. The HIL (Hardware-In-the-Loop) method [13][14] is used for this test. This paper deals with the HIL test of this battery using the real-time model of the hybrid traction subsystem of the studied plug-in hybrid electric vehicle (P-HEV).

Studied vehicle and new battery

A. Low-voltage plug-in hybrid vehicle with original battery
The studied vehicle is a 308 Peugeot SW car that has been retrofitted by Valeo to test an innovative traction subsystem based on a 48V battery and low-voltage electrical machines [12].

The traction subsystem is composed of a thermal engine, 2 electrical drives and a low-voltage (48 V) battery (Fig. 1). For the front part of the vehicle, the 94 kW internal combustion engine and the 4 kW front electrical machine are coupled through a belt. For the rear part, a 25 kW electrical machine drives the rear wheels. Both permanent magnet synchronous machines are supplied by voltage-source-inverters and a 48V battery. This low-voltage hybridization avoids strong modification without specific safety subsystems. The 48V set is enough to improve significantly the fuel consumption [12].

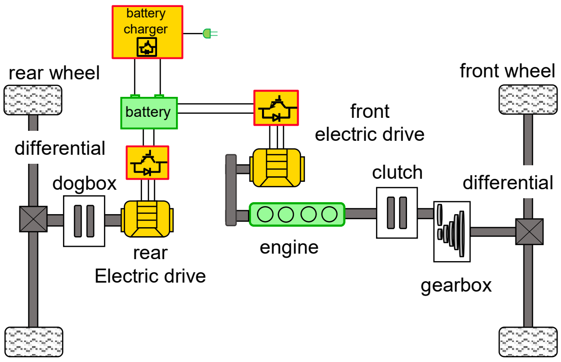

Fig. 1. Hybrid traction subsystems for the studied vehicle

B. New battery to be integrated

An initial self-made Li-ion battery (5 kWh, 111 Ah) has been embedded in the demo-car. The maximal discharge current is 600A (5.4 C). The rated voltage is 44.4 V. As the total battery weight is 50 kg, the energy density is 100 Wh/kg and the power one is 266 W/kg. This energy density seems to be low but it includes the water-cooling system.

A new Li-ion NMC battery is manufactured by the Bluways company. It has a pretty high-power capability (1.92 kW/kg). This amount of power could allow to use it without a cooling system. Thus, in the next sections, the power tests will be achieved without any cooling system to validate this. For a module (Fig. 2), the maximal C-rate is 15 C, the maximal discharge current is 1200 A, the maximal charge current is 240 A. A module is composed of 30 cells that lead to a 142 Wh/kg energy density.

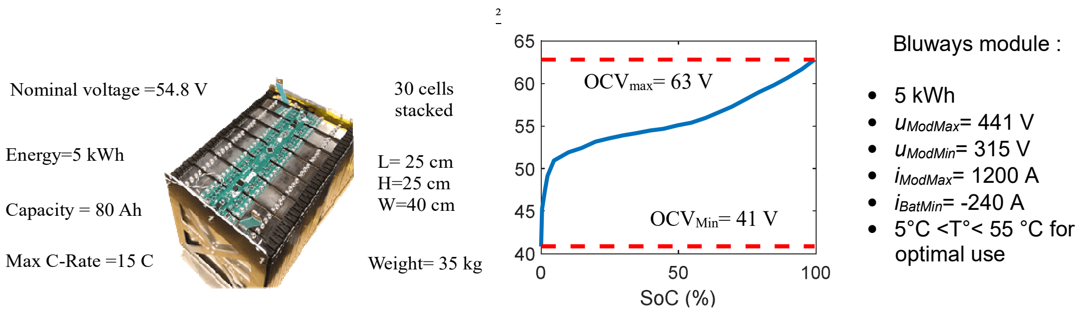

Fig. 2. Characteristic of the new battery module

In order to get the vehicle performances, two battery modules are connected in parallel (Fig. 3) to obtain a 10 kWh energy source that double the capacity for only 70 kg (40% of supplementary mass). The nominal voltage is slightly higher (56 V) that lead to reduces the current peak for the same traction power.

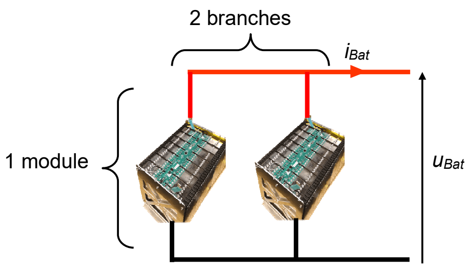

Fig. 3. Battery pack for the studied P-HEV

C. Simulation of the studied P-HEV

First, the complete hybrid traction subsystem is modelled using EMR (Fig. 4) according to the PANDA project. The energy sources are depicted by green oval pictograms (e.g. the battery). The energy conversion elements are depicted by orange pictograms (e.g. the electric drive). The input of the simulation and the power test is the velocity as a function of the time (driving cycle). As a consequence, the velocity should be controlled to generate the right amount of power to the tested battery. The control scheme (light blue pictograms) is directly deduced by an inversion of the EMR [8]. Moreover, an Energy Management Strategy (EMS, dark-blue pictogram) distributes the energy within the subsystem in order to reduce the energy consumption. Equations and details on the control are given in [12].

The hybrid powertrain is then implemented in the Simcenter AMESIM software using the EMR library developed by Siemens within the PANDA project [9]. The simulation model is available in the PANDA cloud.

It can be noted that a static map of efficiency is used for the electric drive in this simulation. However, the PANDA cloud has multi-level models of the electric drive that can be seamlessly interchanged according to the EMR organization, for more in-depth studies [12]. The use of a static map is also a way to preserve the confidentiality of this innovative low-voltage electrical machine.

The simulation study results are given from *Fig. 5 to Fig. 9*. For a WLTC class3 reference cycle (*Fig. 5*) that corresponds to a total cumulated distance of 23.3 km under various conditions (i.e. urban to highway). Simulation results on battery current (*Fig. 7*), battery voltage (*Fig. 8*) show that the electrical limits (Fig. 2, Fig. 3) are not crossed. The evolution of the SoC gives an idea of the driving range in hybrid mode (≈180km). This simulation is used as a pre-validation step. The power test can be achieved in the next section.

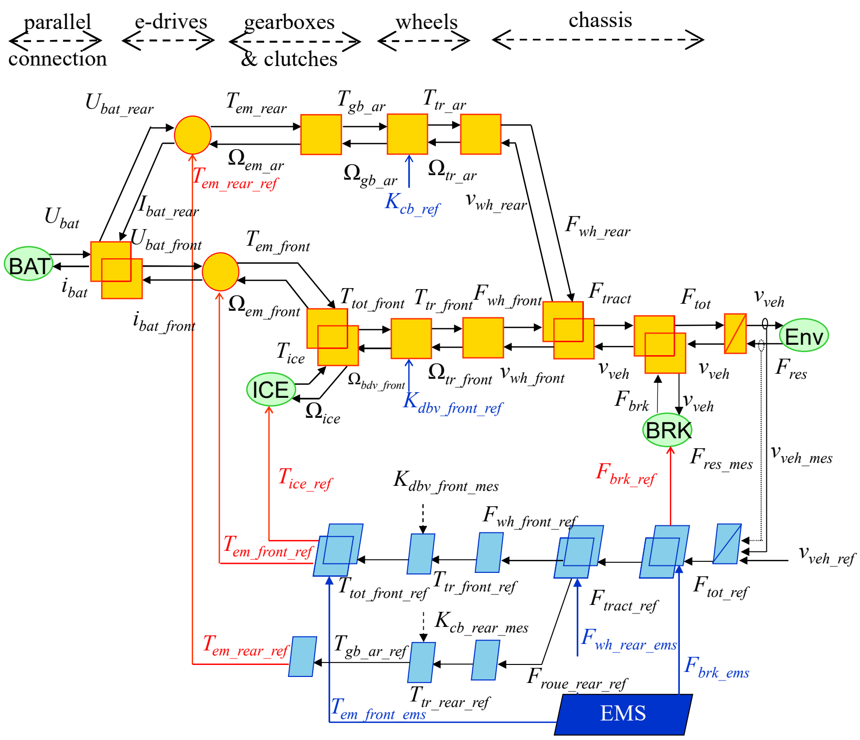

Fig. 4. EMR and control for the studied P-HEV

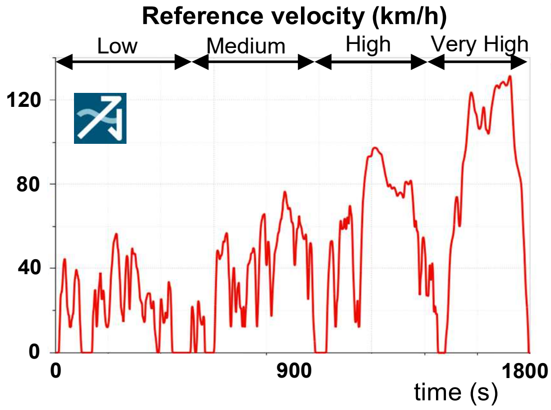

Fig. 5 WLTC reference velocity cycle

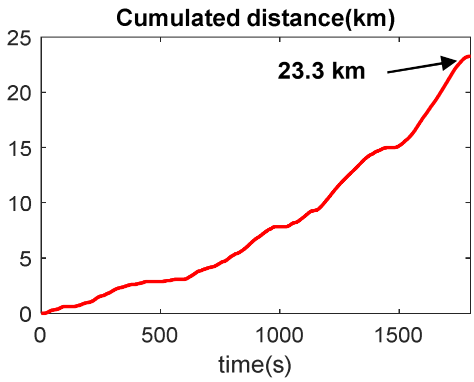

Fig. 6 Cumulated distance

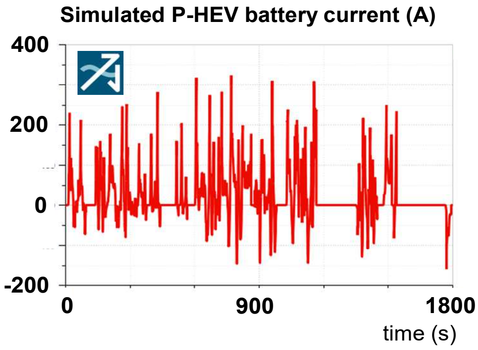

Fig. 7 Simulated battery current

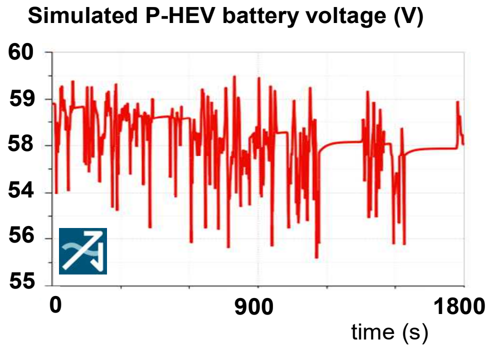

Fig. 8 Simulated battery voltage

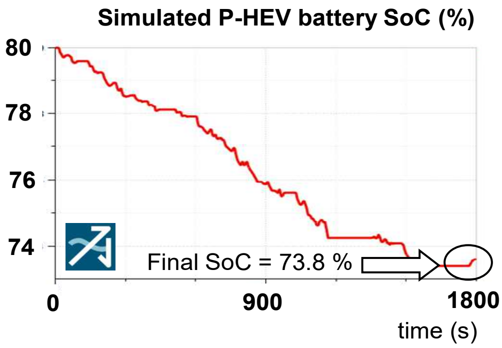

Fig. 9 simulated battery SoC

Power Hardware-in-the-Loop testing

A. Power HIL principle

As the simulation study has given results compatible with the tested battery, the power test is achieved. In order to test the battery, the battery model is replaced by a real battery in the simulation loop (Fig. 10). The hybrid traction subsystem is simulated in real-time in a dedicated ECU (Electronic Control Unit). As the simulation only delivers signal variables, a power amplifier is needed to generate the load current to the tested battery. This power amplifier is an interface between the real device under test and the simulation part.

The power amplifier is a current source and is directly connected to the battery to test. The measured experimental battery voltage is used as an input for the real-time simulation while the current runs through the battery. Thus, there is a real time interaction between the two parts.

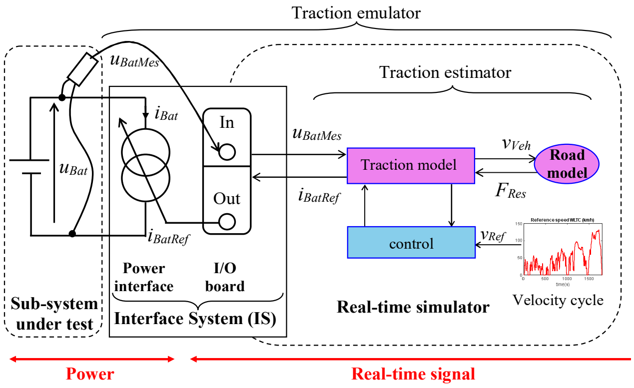

Fig. 10. HIL organization

B. HIL set-up

A Typhoon ECU is in charge of the real-time simulation of the hybrid traction subsystems (Fig. 11). A dedicated compiler has been developed to translate the Simcenter AMESIM model from the cloud to the ECU code. This ECU is connected to a Cinergia power amplifier to generate the load current for the battery. A unique Blueways module is considered in this test and the traction current is divided by two in order to test the module as in the real vehicle (where 2 modules are connected in parallel).

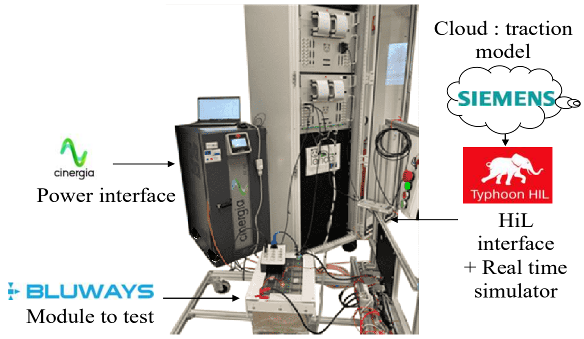

Fig. 11. HIL experimental set-up

C. Experimental results

The same driving cycle is imposed (Fig. 12, Fig. 13) for the power test. One module is tested instead of the whole battery (Fig. 3). The current is measured (Fig. 14). The module voltage measured from the BMS and the voltage imposed to the power amplifier are very close (Fig. 15). The State-of-Charge (SoC) has the same evolution (Fig. 16) than in the pure simulation (Fig. 7). Experimental test allows to get more information than simulation. Here, the experimental test bench is instrumented with thermocouples. Thus, the evolution of the module temperature can be recorded. During the test, the temperature has variation within the battery limits (Fig. 17). This confirms that a cooling system is of no interest with the new battery.

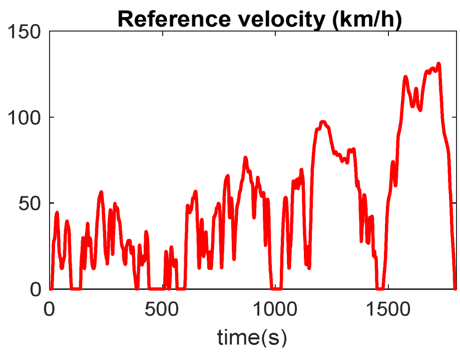

Fig. 12 WLTC reference velocity cycle

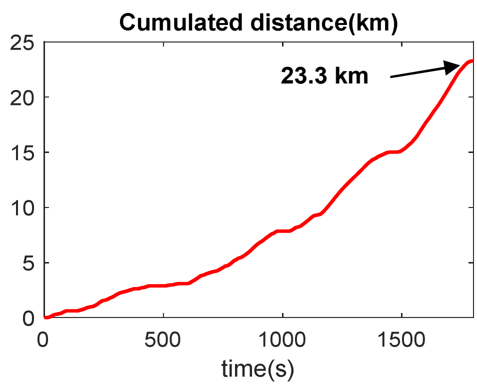

Fig. 13 Cumulated distance

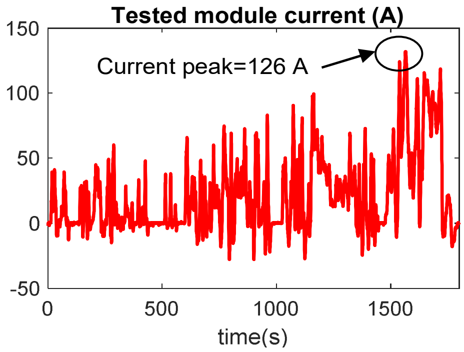

Fig. 14 Experimental module current

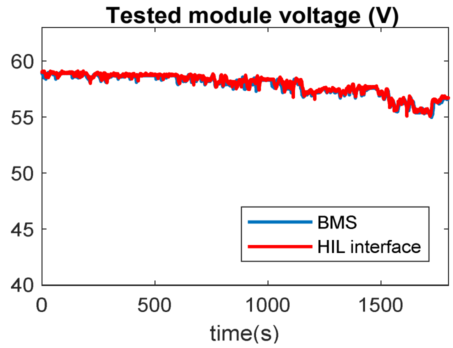

Fig. 15 Experimental module voltage

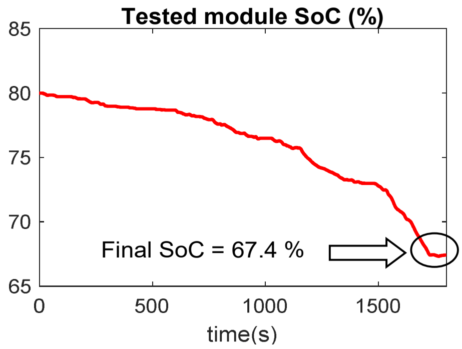

Fig. 16 Experimental module SoC

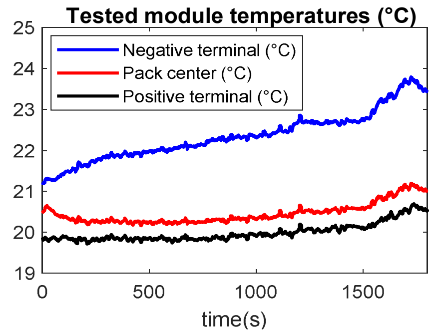

Fig. 17 Experimental temperature

Conclusion

A new battery has been tested before its integration on a demo hybrid electric vehicle. A real-time simulation model has been used for the power hardware-in-the-loop testing of the battery. The new battery can achieve the performances requested by the vehicle. This kind of test also gives additional indications. As a matter of fact the negligible experimental self-heating of the new battery indicates that a cooling system is optional.

Acknowledgment

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