Control validation of Peugeot 3∞8 HYbrid4 Vehicle Using a Reduced-scale Power HIL Simulation

Tony Letrouve*, Walter Lhomme†, Alain, Bouscayrol** and Nicolas Dollinger***

Abstract – The new engineering challenges lead to a control of a vehicle more and more complex. To tackle this issue, Hardware-In-the-Loop (HIL) simulation is used in the development of real-time embedded systems. In this paper, the control of a double parallel hybrid vehicle is validated using a reduced power HIL simulation. A graphical description is used in order to organize the emulation and control. Some experimental results of a versatile testbed are given for the Peugeot 3∞8 HYbrid4.

Keywords: Power HIL Simulation, Double parallel HEV, Control, Graphical description.

1. Introduction

Hybrid Electric Vehicles (HEVs) are developed to reduced fuel consumption of future vehicles [1-2]. Different HEVs have been developed and some of them are nowadays in the market, such as the well-known Toyota Prius. Nevertheless, in order to enable better performances while reducing the fuel consumption, new HEVs are still developing. With the 3∞8 HYbrid4, the world’s first full hybrid diesel-electric commercialized, Peugeot Motion & Emotion counts on this vehicle in order to enter attractively into the hybrid automotive market share. By coupling a diesel power plant with two Electric Machines (EMs), the 3∞8 HYbrid4 is even more complex than the common hybrid gasoline-electric. Therefore, hardware and software parts play a major role in the success of this technology. Due to the complexity, both parts need to be tested before their integrations in a prototype vehicle.

Fig. 1 shows different steps done from simulation to prototype vehicle for on-road testing. For complex system a Hardware-In-the-Loop (HIL) simulation phase is inserted between the simulation and the prototype vehicle. Hardware-In-the-Loop (HIL) simulation is used for validation tests of real-time embedded systems before implementation on actual processes. Contrary to a software simulation, in a HIL simulation one or several parts of the system are replaced by real parts [3-9]. The other devices, which are not directly implemented, are emulated as model in the software simulation.

The subsystems to test must communicate with the emulated parts. An interface system has to be developed to ensure the connection between the hardware and the simulation parts. Two different HIL simulations are commonly defined: signal and power.

The main objective of the signal HIL simulation is to test the well-known Electronic Control Units (ECUs), which control the energy flow through the vehicle powertrain. All the “power” parts are replaced by models in a real-time simulation space. In this case, the interface system manages only signals (hence its name of signal HIL simulation). As the signal HIL simulation, one of the objectives of the power HIL simulation is to test the ECUs but also a physical part of the system. Power HIL simulation is useful to validate new subsystems (including their control) before the connection with the system. In this kind of real-time emulation, a part of the real components is tested (e.g. energy source and subsystem 1 in Fig. 2). The rest of the system is emulated in a real-time simulation.

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environment (e.g. load model and subsystem 2 model in Fig. 2). The interface system (IS in Fig. 2) exchanges power variables between the hardware on test and the real-time simulation environment.

Depending on the complexity and objectives, two scales of power HIL simulation can also be used: the reduced and full scales [10]. The principal advantage of reduced-scale emulation is the use of a versatile testbed, which allows testing different architectures and powers with the same platform for experimentation. Its objectives are to validate the real-time portability of the control developed in simulation and to test some fault-tolerant operations. In a full-scale emulation, the components used in the real system are tested. It enables to validate the control in real-time and some of the power components. Its main drawback is the design of a specific experimental setup, which will be difficult to use for another system.

The objective of this paper is to validate the control of the Peugeot 3×8 HYbrid4 using a reduced-power HIL simulation. For this purpose a versatile experimental setup is used. The simulation of the vehicle has been previously done in [11]. The use of EMR (Energetic Macroscopic Representation) was used to structure the modeling and the control. In order to keep the same method, the EMR approach is reused to structure the HIL simulation.

In section 2, the HIL simulation approach of the hybrid vehicle is presented. Section 3 deals with the experimental results on a testbed. Some discussions about these results are given at the end.

2. HIL simulation of the Peugeot 3×8 HY4

2.1 Studied vehicle

The vehicle is the SUV (Sport Utility Vehicle) Peugeot 3×8 HYbrid4, which combines a hybrid front-wheel drive system and an electrical rear-wheel drive system (Fig. 3). The vehicle can operate in traction, propulsion or 4WD (4 Wheel Drive) mode [12-14]. The electrical rear-wheel drive is achieved by a 27 kW Permanent Magnet Synchronous Machine (PMSM), which allows operating in all-electric mode at low speeds and operate as a generator during braking events to store energy in the high voltage battery. A gearbox and a dog box serve to transmit the drive force delivered by the rear PMSM to the wheels. The hybrid front-wheel drive is achieved by a turbocharged diesel engine and by a 7 kW PMSM coupled with a belt / pulley system. This EM enables the stop and start mode, an electrical boost when the vehicle accelerates, a pure electric traction and the recovery of energy when the vehicle decelerates. A high voltage battery supplies the EMs through inverters and a 12V battery is used for the electrical low voltage accessories. Both batteries are connected together through a DC/DC converter.

2.2 Principle of power HIL simulation

The power HIL simulation of HYbrid4 architecture is represented in the Fig. 4. The ECU (vehicle control) and both EMs (front and rear) are tested. In order to impose the same speed on the mechanical shafts of both EMs, two specific interfaces have to be added to link the shafts and the vehicle shaft model. Two electric drives (EMs plus its power electronics – PE in Fig. 4), controlled in speed, are used to emulate the rear and front powertrains of the vehicle. For the rear wheel drive, the 27 kW PMSM is described by the rear EM. The rear part, from the dog box to the wheels, is emulated with the EM Rear Emulation (Rr. Emul.), which is controlled using the speed reference given by the vehicle model (purple in Fig. 4). For the front wheel drive, the 7 kW PMSM is described by the front EM. The front part, from the pulley / belt system to the wheels (including the ICE), is emulated with the EM Front Emulation (Fr. Emul).

2.3 Reduced-scale power HIL simulation of the HEV

In order to structure the reduced-scale power HIL simulation of the double parallel HEV and to find the interaction variables between the different subsystems, the formalism EMR is used. EMR has been developed to highlight the energy flow in systems and to deduce the control through three principles [15].

Interaction principle – The system is decomposed into subsystems in interactions (see Appendix): energy sources (green ovals pictograms), accumulation elements (orange rectangles pictograms), conversion elements without
energy accumulation (various orange pictograms) and coupling elements for energy distribution (orange overlapped pictograms). All elements are interconnected according to the action and reaction principle using exchange variables. By definition, the product of the action and reaction variables between two elements leads to the instantaneous power exchanged. This property leads to define accumulation elements by time dependant relationships between their variables, in which outputs are integral functions of inputs. Other elements are described using relationships without time dependence.

**Causality principle** – Only the integral causality, i.e. the physical causality, is considered in the EMR philosophy. This property leads to define accumulation elements by time-dependant relationships between their variables, in which outputs are integral functions of inputs. Other elements are described using relationships without time dependence.

**Control principle** – Different steps are required to deduce an inversion control structure from the EMR of the system. This inversion methodology is a way to locate controllers and measurements (or estimations). First, the tuning paths of the system, which link the tuning inputs to the objectives (outputs to control), are defined. Then, these tuning paths are inverted step-by-step by using inversion rules. The relationships without time-dependence (conversion elements) are directly inverted (with neither controller nor measurement). As the derivative causality is not allowed, a direct inversion of time-dependence (accumulation elements) relationships is not possible: an indirect inversion is done using a controller and measurements. Moreover, the inversions of coupling elements require distribution inputs to distribute the energy flow.

From the EMR of the vehicle described in [11] and the HIL simulation principle explained before, the EMR of the reduced-scale power HIL simulation is described in the Fig. 5. A velocity controller, which represents the driver behaviour, is required to define the traction force $F_{\text{trac-ref}}$.

The mechanical coupling, which couples the brakes and the rear and front wheel drives, is then inverted using a distribution input vector $k_{d,fr,rr}$:

$$
\begin{align*}
F_{\text{brakes-ref}} &= k_{d,br,fr} F_{\text{tot-ref}} \\
F_{\text{trac-ref}} &= (1 - k_{d,fr,rr}) F_{\text{tot-ref}} \\
F_{f,wh-ref} &= k_{d,fr,rr} F_{\text{fract-ref}} \\
F_{r,wh-ref} &= (1 - k_{d,fr,rr}) F_{\text{trac-ref}}
\end{align*}
$$

The distribution input vector $k_{d,fr,rr}$, $k_{d,rr,br}$ is necessary to distribute the energy between the brakes and the transmissions ($k_{d,br,fr}$) and between the rear and front-wheel drives ($k_{d,fr,rr}$). The value of this vector changes in
function of the strategy chosen. Another distribution input \( (k_{\text{fem-adapt}}) \) is also required to split the energy between the ICE and the front EM at the front of the vehicle. Other details about modeling and control of the vehicle are given in [11].

The vehicle model is in purple color as it represents the emulation part. The rotation speeds of the two EMs, \( \Omega_{\text{fem-adapt}} \) and \( \Omega_{\text{rem-adapt}} \), induced by the vehicle model are imposed as references to the interface systems. Both electric drives are controlled to achieve the required rotation speed to the rear and front EMs. Adaptation interfaces (in red) are added because of the reduced-scale. Power Adaptations (PAs) are chosen in order to respect the power ratio between the full-scale and the reduced-scale parts. In this way, non-linear effects can be properly taken into account [10]. The PAs must take the limitation of the reduced-scale variables (e.g. maximum speed) into account before the limitation of the full-scale variables. For both EMs tested (rear and front EMs), the torque measurements are required as inputs for the mechanical model. In experimentation, the torque could be estimated from the measurement of the EM currents. The PAs are defined as follows:

\[
\begin{align*}
T_{\text{fem-adapt}} &= k_{\text{fem}} T_{\text{fem}} \\
\Omega_{\text{fem-adapt}} &= k_{\Omega_{\text{fem}}} \Omega_{\text{fem}} \\
T_{\text{rem-adapt}} &= k_{\text{rem}} T_{\text{rem}} \\
\Omega_{\text{rem-adapt}} &= k_{\Omega_{\text{rem}}} \Omega_{\text{rem}}
\end{align*}
\]

with \( k_{\text{fem}}, k_{\Omega_{\text{fem}}}, k_{\text{rem}}, k_{\Omega_{\text{rem}}} \) respectively the adaptation ratios for the front and rear EMs. An inversion of (3) and (4) are required to obtain the references of the experimental torques \( T_{\text{fem-ref}} \) and \( T_{\text{rem-ref}} \) from the references of the model torques \( T_{\text{fem-ref-adapt}} \) and \( T_{\text{rem-ref-adapt}} \):

\[
\begin{align*}
T_{\text{fem-ref}} &= T_{\text{fem-ref-adapt}} / k_{\text{fem}} \\
T_{\text{rem-ref}} &= T_{\text{rem-ref-adapt}} / k_{\text{rem}}
\end{align*}
\]

3. HIL Simulation Results and Discussion

3.1 Experimental setup

For the implementation of the real-time control (Fig. 6), only blue (control vehicle and interface control) and purple blocks (model vehicle) from the Fig. 5 are kept. The HIL simulation platform (Fig. 7a) is composed of two testbeds. Each of them is equipped of one 1.5 kW Direct Current Machine (DCM) and one 1.5 kW Induction Machine (IM) with their associated power electronics. A DSP card (dSPACE DS1005) controls the EM drives. A real-time management of this platform has been achieved using a human-machine interface (Fig. 7b). For the rear-wheel

\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig6.png}
\caption{Real-time control and model of the HIL simulation}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{(a) HIL simulation platform; (b) Human-machine interface}
\end{figure}

drive, the 27 kW PMSM is represented by the 1.5 kW DCM1 (first testbed). The rear part, from dog box to the wheels is emulated by the 1.5 kW IM1. For the front-wheel drive, the 7 kW PMSM is represented by a 1.5 kW IM2. The front part, from the pulley / belt system to the wheels (including the ICE) is emulated by the 1.5 kW DCM2.

3.2 Experimental results

The reduced-scale power HIL simulation of the HEV has been carried out for one UDC (Urban Driving Cycle) followed with one EUDC (Extra Urban Driving Cycle). The experimentation results are given Fig. 8. The strategy considers only one power flow for each operating modes. For example, only the rear EM is used for the modes of regenerative braking and all electric
During EUDC, the ICE starts and gives all the torque. The EMs do not give torque during acceleration phase but they are used during steady-state phase (275 s > t > 360 s).

3.3 Discussion

Compared to the software simulation, a real controller board is used for the HIL simulation. Therefore, the influence of the sampling period and of the quantification of the sensors is taken into account. Moreover, even though the power is reduced, the different power flows between components are tested in different operating modes. The control and the strategy developed in real-time are consequently validated in real time, and they can be tested on a prototype vehicle afterwards.

Compared to the prototype, the HIL simulation allows the test of the real systems with a reduced cost. If a reduced-scale real-time laboratory testbed is already available, many kinds of HEV can be emulated with the same platform. The HIL simulation is a versatile experimental support with fully open control, in which all variables can be measured or estimated. In the prototype vehicle many hardware parts are designed by a component manufacturer (e.g. electric drive). This leads to have some no-access variables (e.g. EM currents) that do not go to the CAN bus. Finally, different kinds of test can be repeated identically safely and in a safety area.

In this paper, since a reduced-scale real-time laboratory testbed is used, the development cost is weak. Compared to the full-scale, the reduced-scale testbed is then versatile because of the possible test of different powertrains and systems. The reduced-scale power HIL simulation is a step to well organize the full-scale, which could be achieved afterwards.

4. Conclusion

A power HIL simulation of the double parallel Peugeot 3×8 HYbrid4 has been validated by a reduced-scale testbed. The control of the ECU and both electric drives (front and rear wheel drives) of the HEV, which were first designed in simulation, has been tested successfully without any change. This kind of HIL simulation has a low cost advantage.

The advance of this research is the demonstration that a complex diesel HEV can be emulated through a systemic approach (i.e. the study of systems and their interactions). The use of EMR as graphical description leads to an organization of the control required for this complex HIL simulation. This approach divides a complex system into several manageable parts, reduces the development time and ensures the system performances. In future prospects, the developed control will be implemented on the prototype vehicle for on-road testing.

Tony Letrouve, Walter Lhomme, Alain, Bouscayrol and Nicolas Dollinger

Fig. 8. HYbrid4 reduced-scale HIL Simulation results: (a) Vehicle speed, (b) Position of the clutch; (c) Rear EM speed; (d) Front EM speed; (e) Front EM torque; (f) Rear EM torque; (g) ICE torque; (h) Emulated SoC; (i) Operating mode during this mode).
Appendix: Synoptic of Energetic Macroscopic Representation

<table>
<thead>
<tr>
<th>Source of energy</th>
<th>Mono-physics coupling</th>
<th>Mono-physics converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Element with energy accumulation</td>
<td>Multi-physics converter</td>
<td>Emulated part</td>
</tr>
<tr>
<td>Coupling inversion block</td>
<td>Control block with controller</td>
<td>Adaptation block</td>
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References


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