PHEBUS Vehicle: a small urban PHEV

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***Abstract* – This paper presents a small urban plug-in hybrid electric vehicle whose propulsion architecture includes a conventional internal combustion engine connected with a continuously variable transmission in the front wheels and two in-wheel electric machines in the rear wheels. Various operation modes, including zero emission vehicle mode, boost mode, and regenerative braking mode, are possible with this solution. In this paper, the authors describe the different components used in the vehicle and the different operating modes. First experimental results, in particular the ones concerning the regenerative braking, are shortly presented at the end of the digest.**

Keyword: Plug-in Hybrid Electric Vehicle; energy storage system; in-wheel motor; energy management; experimental test

I. INTRODUCTION

The exhaustion, increased cost and location of fossil fuels on the one hand, and the environmental problems caused by emissions of CO2 in the atmosphere on the other hand, leads to a change of technology choices in transportation. An ideal solution would be to use an electric vehicle (EV) whose batteries would be recharged with renewable electricity. An EV powered by a fuel cell could be a good solution too, if H2 is produced with renewable energy. Unfortunately, poor specific energy and power of batteries, and low lifetime of fuel cells impose to develop intermediate technological solutions such as hybrid electric vehicle (HEV) [1]. Beside, the recharge of batteries enables to reach a good autonomy in all-electric mode; then, this newtype of vehicle is named plug-in HEV (PHEV) [2]. In this context, the French project PHEBUS (Bi-mode Hybrid Electric Propulsion for Urban uSe) consists in the complete development of a PHEV with an original powertrain. This latter uses a classical internal combustion engine (ICE) in the front wheels and two in-wheel electric machines in the rear wheels. It has been performed on the basis of an existing thermal vehicle. The changes are to integrate two motors into the back wheels and to place the energy source system (ESS), including here lead-acid batteries and ultra-capacitors, under the floor. Simple but practical operation modes are possible with this solution to enhance the vehicle performances, to increase the fuel economy and to reduce the emissions: boost mode, zero emission vehicle (ZEV) mode, regenerative braking mode, etc. Moreover, the ICE can be downsized thanks to the introduction of electric machines, which further reduces the fuel consumption and the CO2 emissions.

In the section II, we will present the architecture and the different operating modes of the vehicle 'PHEBUS'. Then, in the sections III, the technical specifications are described. In the section IV, the different components are shortly presented, including the in-wheel motors, the ESS, the power electronic and the energy management system. Finally, in the section V, the authors focus on experimental results and in particular regenerative braking.

II. ARCHITECTURE AND OPERATING MODES OF THE VEHICLE 'PHEBUS'

1. *Architecture of the vehicle*

The architecture of the hybrid propulsion used in PHEBUS is presented in Fig. 1 [3]. The main idea is to involve a conventional ICE connected with a continuously variable transmission (CVT) in the front wheel. The ICE can be downsized, because two permanent magnet synchronous machines (PMSMs) are integrated directly into the rear wheels.

The two energy sources are the fuel tank (thermal source, non reversible) on the one hand, and the batteries and the ultra-capacitors (electric source, reversible) on the other hand. These two sources can operate independently (in thermal mode or in electrical mode) or the power generated by these sources can be added (boost mode) or subtracted (regenerative braking). In that sense, PHEBUS is a parallel

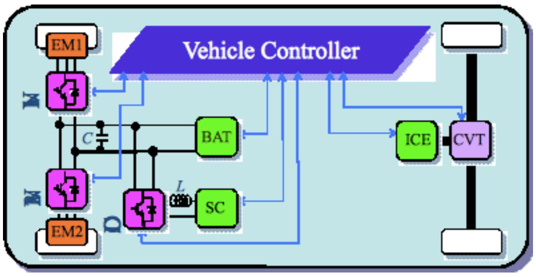


Fig. 1. Architecture of the 'PHEBUS' vehicle

HEV and the coupling of the thermal and electric powers is performed via the road. This is a simple way to achieve the coupling, instead of complex mechanical devices such as epicyclic gearing in Toyota Prius [4].

2. *Operating modes of the vehicle*

The architecture described above enables the following different operating modes.

Thermal mode

In this mode, the thermal engine drives the vehicle and the energy is provided by the fuel tank. This mode is interesting in suburban zone to keep an interesting autonomy of around 300 km. The maximal speed is 65 km/h and, if the ICE is downsized, this maximal speed can be reached by using the hybrid boost mode (see hybrid mode).

Electric mode

In this mode, the two in-wheel motors drive the vehicle and the energy is provided by the ESS (battery + ultra-capacitors.) This mode is preferred in downtown because it is a zero emission mode. The maximum speed is limited to 50 km/h.

Hybrid mode

In this mode, both ICE and electric machines are used. Two cases are possible. In the first case, the mechanical powers coming from the ICE and the electric machines are both used to drive the vehicle. This enables to recover the accelerations or the maximal speed of the initial thermal quadricycle, with a downsized ICE. This mode is called *boost* mode. The second case deals with the regenerative braking. Indeed, the reversibility of the in-wheel electric machines and the electric ESS enables to slow down the vehicle by recovering the kinetic energy in the ESS. This is used to simulate the classical engine brake in both electric and thermal modes and it is also used to enhance the braking. With the regenerative braking, the energy consumption is reduced and the brakes are saved.

Recharging mode

Since PHEBUS is a plug-in hybrid vehicle, the batteries can be recharged by plugging the vehicle into an electric outlet. To achieve that, a commercial charger has beeninstalled in the vehicle (see §IV.D). This mode enables to increase the vehicle autonomy in electric (i.e. zero emission) mode. In this mode, the energy is provided by an electric network, and it is possible to use preferentially green electricity.

III. TECHNICAL SPECIFICATIONS OF THE VEHICLE

PHEBUS has been implemented in a commercial quadricycle provided by the French company AIXAM-MEGA (see Fig. 2). The main technical features of this vehicle are summarized in the Table 1. To size the different power and energy components of this hybrid vehicle (electric machines, ESS, power electronic...), different particular missions have been defined according to the experience of the manufacturer AIXAM-MEGA. Those missions deal with maximal acceleration, hill start, to rise of sidewalk, electric braking... These missions have been simulated with using a software of vehicle dynamics simulations. This latter enables the simulation of the dynamic mechanical behavior of the vehicle.

Fig. 2. The quadricycle of AIXAM-MEGA Company used to develop PHEBUS

TABLE I
TECHNICAL FEATURES OF PHEBUS

Vehicle length	3'000 mm
Vehicle width	1'520 mm
No-load weight (without batteries)	480 kg
No-load weight (with batteries)	600 kg
Maximal weight (with load)	900 kg
Maximal speed (thermal mode)	65 km/h
Maximal speed (electric mode)	50 km/h
ICE power	(400 cm^3) 6 kW

We summarize hereafter the vehicle specifications for the two main modes (electric and thermal).

Electric mode

The maximal speed is limited to 50 km/h and the autonomy has to be at least 30 kms. The acceleration from 0 to 45 km/h should be achieve in less than 10 s. The vehicle should start and reach a speed of 10 km/h in 6 s on a road with a slope of 16%. The vehicle must cross a sidewalk with an initial velocity greater than 2 km/h.

Thermal mode

Thermal propulsion is provided by a twin diesel engine of 400 cm^3 and 6 kW, knowing that the regulatory framework imposes a total engine power (thermal engine + electrical motor) lower than 15 kW. The maximal speed is 65 km/h and the autonomy has to be at least 300 km/h.

IV. DESCRIPTION OF THE DIFFERENT VEHICLE COMPONENTS

The main components of the vehicle are described in this section.

1. *In-wheel motors*

The two in-wheel motors are surface mounted permanent-magnet (PM) machines. The different electromagnetic parts of the motors are illustrated in Fig. 3. The motors are integrated in standard 15" wheels, the maximal torque equals to 240 N.m per motor (direct drive), the maximal power equals to 4,5 kW per motor and the rotating speed equals to 616 rpm at the maximal vehicle speed of 65 km/h (thermal mode) [5].

2. *Batteries and ultra-capacitors*

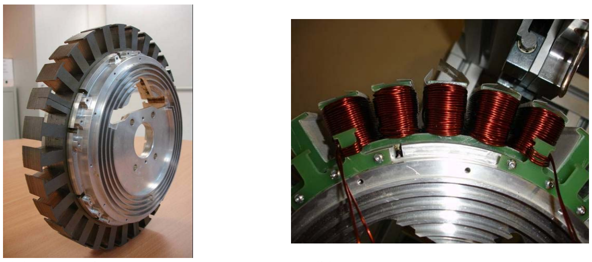
The ESS is made of 18 units of 12 V - 20 A.h lead acid batteries (reference 6-DMZ-20 of ABT Company) and 14 modules of 15 V - 58 F ultra-capacitors (reference BMOD0058 E015 B1 of Maxwell Company) [3]. The maximal voltage of the batteries pack is 243 V and the energetic capacity equals to 4.9 kW.h (for rated current). Regarding the ultra-capacitors, their maximal voltage is 210 V and the energetic capacity is approximately 20 W.h. The batteries and the ultra-capacitors can receptively deliver maximal currents of 30 A (at 200°C) and 80 A (during 1 s).

3. *Power electronic*

The power electronic has been specifically developed by the French Company CIRTEM. It includes two voltage source inverters (one for each in-wheel motor), a DC/DC buck converter for the control of ultra-capacitor energy and another DC/DC buck converter to recharge the auxiliary battery. The only input information coming form the vehicle controller is the desired torque that the two electric motors have to provide.

4. *Battery charger*

To recharge the power batteries, a commercial recharger is embedded in the vehicle. Its reference is NLG5 from the Swiss company Brusa. The output power is 3.2 kW and it enables to recharge the complete batteries pack in around 5 hours.



(a) stator laminations *(b) stator concentric windings*

(c) external rotor with surface mounted PM *(d) the in-wheel motor*

Fig. 3. Architecture of the 'PHEBUS' vehicle

5. *Vehicle controller*

The vehicle controller has been specifically developed by the French Company NSI. It includes different electronic cards to measure precisely the voltage and the current of the batteries and the ultra-capacitors, and also a real-time programmable controller with both analog and digital inputs and outputs. All the communications between the different components use the standard CAN bus. The controller enables to achieve the supervision of the whole vehicle and, in particular to calculate the desired torque that the power electronic and the electric motors have to provide to drive or to slow down correctly the vehicle. The program of the supervisor can be simply developed in Matlab/Simulink environment on a PC and the program is then compiled, built and exported to the real-time supervisor automatically. This simplify the tuning of the energy management strategy, of the drivability (shape of the motor torque references for example)...

V. EXPERIMENTAL RESULTS

In this last paragraph, we present first experimental results, and, in particular, a focus on the regenerative braking.

1. *Flat road maximal speed in electrical mode*

The vehicle speed is recorded during a test in electrical mode on a flat road and without wind. The chronogram of the speed is given in Fig. 4. It shows that a maximal speed of 52 km/h has been reached during this test, proving that the desired specifications are obtained. The vehicle can be used in downtown where the maximal speed generally does not exceed 50 km/h.

2. *Flat road constant speed in electrical mode*

A second test has been achieved in electrical mode. It consists in driving on a flat road at nearly constant slow speed (around 18 km/h). The results of this test are presented in Fig. 7: vehicle speed and battery voltage, current and power are plotted during the whole test. It can be shown that a power of around 1’500 W is sufficient to get this speed in this conditions. Then, an energy consumption of 25 W.h per minute is sufficient to maintain a speed of around 18 km/h on a flat road without wind.

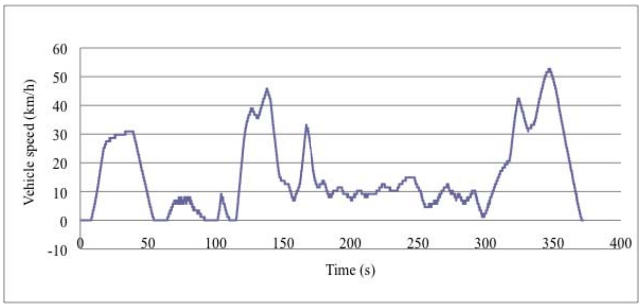
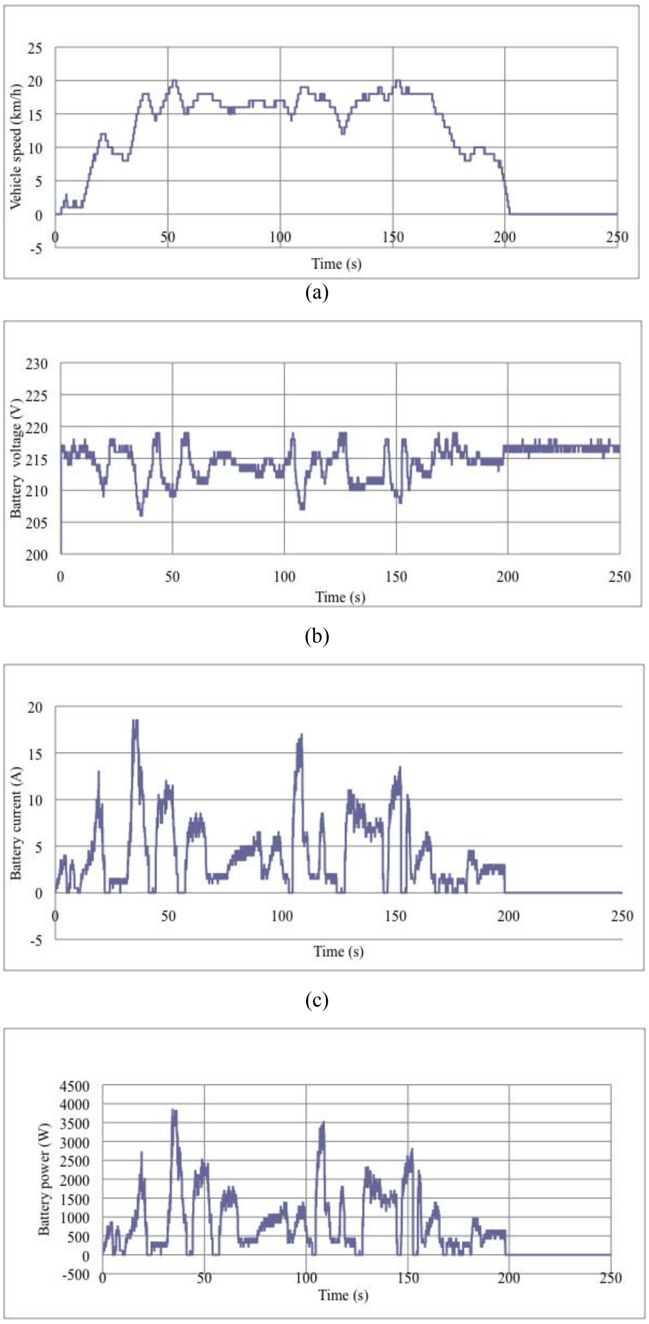


Fig. 4. Evolution of the vehicle speed during a test in electrical mode on a flat road and without wind



(a)

(b)

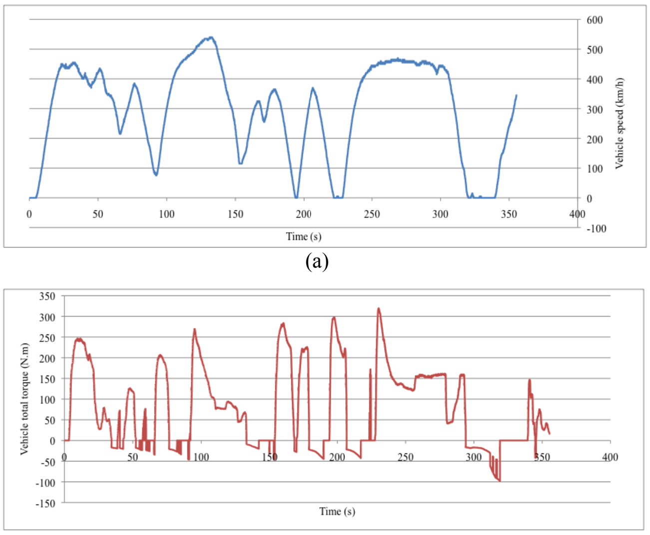
(c)

(d)

Fig. 5. Results of a test at constant speed (18 km/h) on a flat road and without wind: (a) Vehicle speed – (b) Battery voltage – (c) Battery current – (d) Battery power

3. *Thermal mode with boost function*

We present here the results of a test in hybrid mode, i.e. in thermal mode using boost function. During this test, the ICE is driving the vehicle and the in-wheel motors are periodically used to get additional acceleration. We present in Fig. 6 the evolution of vehicle speed and total torque. When the boost is enabled, the total torque becomes higher than 200 N.m and a strong acceleration can be observed: the vehicle speed accelerates from 0 to 40 km/h in less than 8 s.



(a)

(b)

Fig. 6. Results of a test in thermal mode with boost function: (a) Vehicle speed – (b) Vehicle total torque

4. *Regenerative braking*

Principle and strategy

The simplest strategy is implemented in PHEBUS. The ultra-capacitors current is controlled to keep the batteries current equal to 0 A, when the ultra-capacitors voltage is between Umax/2 = 100 V and Umax = 200 V. Otherwise, the ultra-capacitors current is null. In other words, if possible (i.e. if the ultra-capacitors energy is between Emax/4 and Emax), the energy exchanges are performed by using the only ultra-capacitors; otherwise, the batteries are used. This strategy has the advantage of simplicity, but its main drawback is the fact that, when the batteries are used, those latter have to provide currents with strong variations, leading to a reduction of the batteries lifetime. Other energy managements are possible to maximize the lifetime of the batteries [6].

Experimental results

We present here results corresponding to an electric mode with different accelerations and decelerations (maximal speed of around 40 km/h). During the deceleration, a first step deals with a simulation of the ICE braking (when the driver doesn't push on the braking pedal), and a second step deals with the real braking. In the first step, the supervisor imposes a deceleration with a constant torque of -50 N.m (-25 N.m per motor) and, during the second step, when the driver pushes on the braking pedal, an electrical braking with a constant torque -100 N.m (-50 N.m per motor) is imposed in addition with the mechanical braking. The evolution of the main operating parameters (vehicle speed, motors torques, ultra-capacitors voltage) are plotted in Fig. 7. The energy recovery is highlighted by the increase of the ultra-capacitors voltage.

Finally we present in Fig. 8 a longer test where the energy recovery is larger: during this test, the UC voltage increases up to 132 V, corresponding to a recovered energy of approximately 5.5 W.h in the ultra-capacitors.

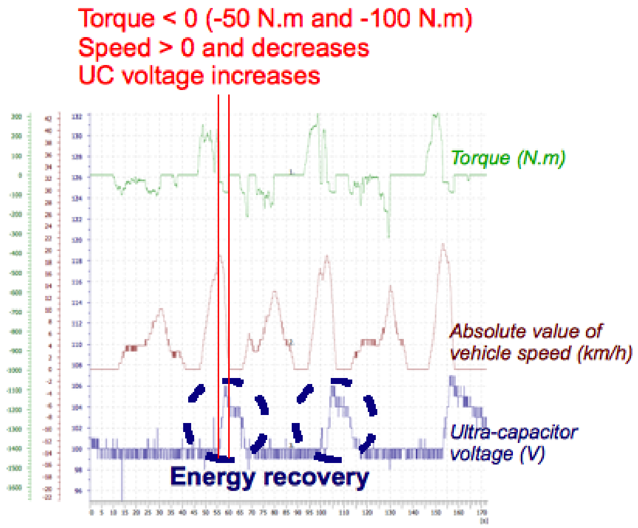


Fig. 7. Experimental result of regenerative braking (principle)

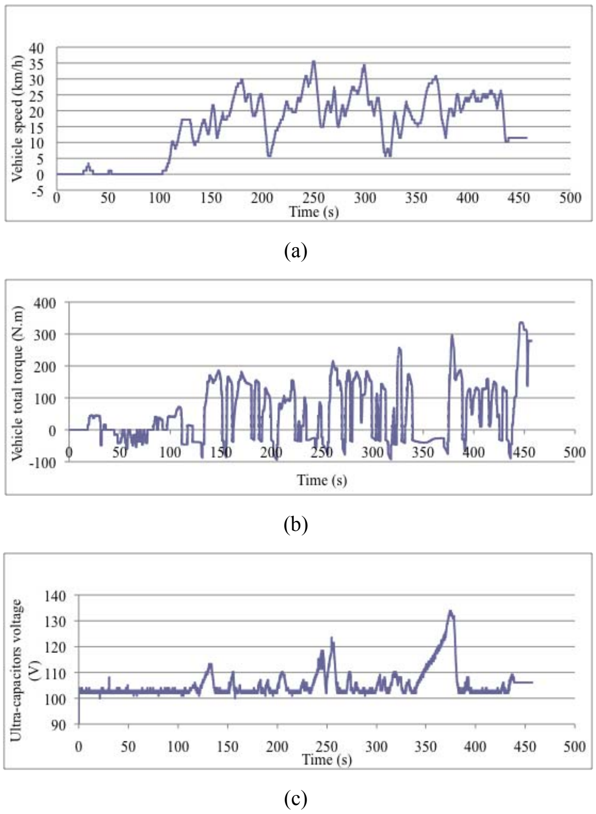


Fig. 8. Experimental result of regenerative braking (large energy recovery)

VI. CONCLUSIONS

In this paper, a small PHEV has been described. The architecture of the vehicle enables three different features: zero emission mode in downtown, large autonomy (300 km) out of the town and a down-sizing of the ICE. Regarding the ESS, a simple energy management strategy has been implemented using only one power converter to control UC and batteries energies. Experimental results have been provided to illustrate the vehicle performances, and in particular the regenerative braking. The main results are:

- Maximal speed of 52 km/h has been measured on a flat road in electrical mode;
- Mean energy consumption on a flat road at the stabilized speed of 18 km/h is around 25 W.h per minute;
- The use of both ICE and in-wheel motors enables accelerations of 40 km/h in less than 8 s on flat road;
- Regenerative braking using the in-wheel motors enables to simulate the engine brake and to enhance the mechanical brake, while recovering kinetic energy.

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