Sizing and experimental characterization of ultra-capacitors for small urban hybrid electric vehicle

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Abstract - **This paper presents the design and the experimental tests of an ultra-capacitor pack used as an energy storage system in a small hybrid electric vehicle. This design consists in calculating the capacitance and the power of the capacitors, which are necessary to store kinetic energy during deceleration of the vehicle and then to accelerate the vehicle. In a second part, experimental tests are achieved to determine the real parameters of the capacitor pack electric model [1] in order to validate the manufacturer data. Influence of temperature on those experimental data is investigated too. Finally, the authors determine the energetic behaviour of the ultra-capacitors: they have measured an efficiency of around 95% during capacitors charge and discharge.**

Keywords – ultra-capacitor (UC); energy storage system; hybrid electric vehicle (HEV); experimental tests

I. INTRODUCTION, 'PHEBUS' VEHICLE

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 whose batteries would be recharged with renewable electricity. The electric vehicle powered by a fuel cell can be a good solution too, if H2 is produced with renewable energy. Unfortunately, poor performances and low lifetime of batteries and fuel cells impose to develop intermediate technological solutions such as hybrid vehicle. In this context, the French project PHEBUS (Bi-mode Hybrid Electric Propulsion for Urban uSe) consists in the complete development of a hybrid vehicle with an original powertrain.

The project aims to design such a new HEV type with a classical thermal engine in the front wheels and two in-wheel electric machines in the rear wheels. It could be performed on the basis of an existing thermal vehicle. The changes are to integrate two motors into the back wheels and to place its energy source system (including lead-acid batteries and ultra-capacitors) under the floor. Simple but practical operation modes are possible in this solution to enhance the vehicle performances, increase the fuel economy and reduce the emissions, for example, BOOST mode, ZEV (zero emission vehicle) mode, and regenerative braking mode, etc. A downsized engine is resulted due to the introduction of electric machines, which further reduces the fuel consumption and the emissions. This new hybrid propulsion architecture is presented in Figure 1. It is quite different from other designs not only considering its architecture but also considering its energy management. The main idea is to involve a conventional thermal engine connected with a continuously variable transmission (CVT) in the front wheel. The ICE can be downsized by using two permanent magnet synchronous machines (PMSMs) directly integrated into the rear wheels. The hybrid architecture makes these working modes possible: ZEV mode (all-electric mode), thermal mode (the in-wheel motors are only used to recover energy during deceleration), and hybrid mode. The electric machines can also operate in electric generators during regenerative braking phase even at low speeds. The braking energy charges the ultra-capacitors (UC) through a dual-directional DC/DC chopper and the lead-acid batteries (BAT) if necessary thus enhancing the vehicle autonomy. The batteries could also be recharged on the grid through an on-board charger (not shown in figure 1). Furthermore, in hybrid mode, the powers from the two machines can be used to enhance the acceleration performance (BOOST function). In this vehicle, the electric energy storage is made of both lead batteries and ultra-capacitors. The battery is used as an energy source while the ultra-capacitors operate as a reversible power source, making it possible to realize very constrained cycles with quick starts and fast decelerations, as it is necessary in the case of urban use. The ultra-capacitors are devices for energy storage that can provide very high power, leading to very quick charge and discharge. They are used in PHBUS to provide sufficient power to the wheel motors during acceleration and to recover kinetic energy during vehicle braking (or deceleration). The ultra-capacitors are not able to store as much energy as in batteries but they can deliver it faster. In other words, the specific power of ultra-capacitors is higher than the one of batteries, whereas the specific energy is lower.

In this paper, the authors will first present the ultra-capacitors sizing considering the particular case of the hybrid vehicle PHEBUS. This sizing consists in calculating the ultra-capacitors capacity value, which makes it possible to recover energy coming from the vehicle deceleration and to reuse this energy to accelerate the vehicle.

To achieve this calculation, two methods are used:

- in the first one, the powers to provide and to recover energy in the capacitors, the maximum voltage and the working times (times of charge and discharge) are fixed according to the specifications;

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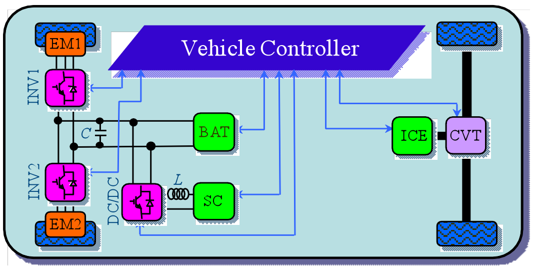

Fig. 1 Structure of the vehicle

- in the second method, a typical normalized profile is used to define the energy and power characteristics of the ultra-capacitors (knowing the working mass of the vehicle).

In a second part of the paper, the authors present results of experimental tests that have been done with the sized ultra-capacitors. Those tests was performed to characterize the ultra-capacitors in order to:

- validate the parameters given by the manufacturer;
- determine the ones of an equivalent electric model to achieve later simulations;
- validate the energy behaviour of the capacitors during charges and discharges.

II. DESIGN OF ULTRA-CAPACITORS

A. First approach

A first approach has been considered to size the ultra-capacitors. This simplified approach consists in calculating the energy and power needed to accelerate the vehicle from 0 km/h to the maximal speed and the energy and power that can be recovered during the deceleration of the vehicle from the maximal speed to 0 km/h; in this case, the requirements of the energy storage system are directly deduced from this calculation, without taking into account driving cycle.

Figure 2 illustrates the different steps of the ultra-capacitors sizing calculations and the selection criteria [2].

In the traction mode, the maximal power in the capacitors equals to

$$P_{\max} = P_{motor} / \eta_{T1} \tag{1}$$

where P_{motor} is the power delivered by the electric machine and η_{T1} is the global efficiency of DC/DC converter, the inverter and the in-wheel motor (for the sizing, the ideal case of $\eta_{T1}=1$ is considered). If Δt is the duration to accelerate the vehicle from 0 to 65 km/h, the energy can be calculated by

$$E = P_{\max} \cdot \Delta t \tag{2}$$

Finally, the voltage U_{scmax} is fixed by the specifications of the vehicle (200V).

In the recovery mode, the maximal power Pmax is determined with the kenetic energy of the vehicle. The equations to calculate the Pmax are the following:

$$E_C = \frac{1}{2} \cdot M \cdot v^2 \tag{3}$$

$$E_{\max} = \eta_{T2} \cdot E_c \tag{4}$$

$$P_{\max} = \frac{E_{\max}}{\Delta t} \tag{5}$$

where E_{max} is the energy that can be recovered in the capacitors and η_{T2} the global efficiency of in-wheel motor (acting as a generator), inverter (acting as rectifier) and DC/DC converter (as for the traction mode, we consider $\eta_{T2}=1$). The others parameters given in Table 1 is determined by:

$$U_{sc\min} = \frac{U_{sc\max}}{2} \tag{6}$$

$$I_{sc\max} = \frac{P_{\max}}{U_{sc\min}} \tag{7}$$

$$I_{sc\min} = \frac{P_{\max}}{U_{sc\max}} \tag{8}$$

$$I_{moy} = \frac{I_{sc\max} + I_{sc\min}}{2} \tag{9}$$

$$C_t = \frac{I_{moy} \cdot \Delta t}{U_{sc\max} + U_{sc\min}} \tag{10}$$

$$N_P \cdot C_{Cell} = N_s \cdot C_t \tag{11}$$

$$N_s = U_{s\max} / U_{cell} \tag{12}$$

$$E_{tsc} = 1/2 \cdot C_t \cdot U_{sc\max}^2 \tag{13}$$

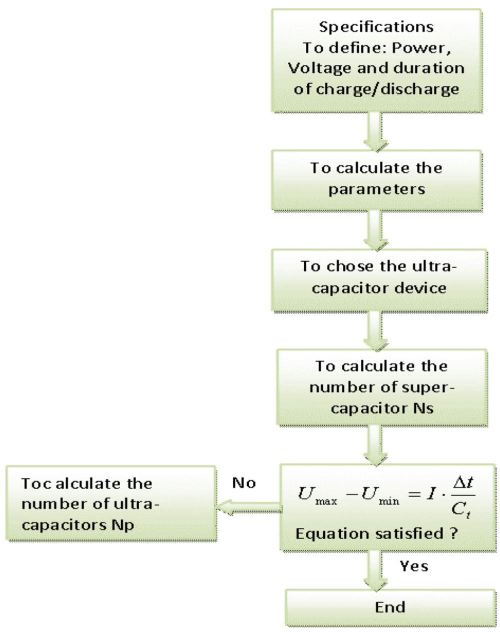

Fig. 2 Ultra-capacitors sizing algorithm

The calculation results are given in the table 1. It makes it possible to define the characteristics of one ideal ultra-capacitor. After that, it is necessary to find a real component or pack of components, which is able to fulfill the previous requirements. The Maxwell capacitors have been investigated and the choice has been made according to the following criteria:

$$C_{cell} \leq C_{datasheet} \quad I_{scmoy} \leq I_{datasheet} \quad E_{tsc} \leq E_{datasheet}$$

Figure 4 presents the comparison of two possible components: the parameters of BCAP650 are better in comparison with BCAP350 and the BCAP650 corresponds to the selection criteria, but finally the BCAP350 have been chosen since there is only a small difference with the performances obtained with the ideal capacitor parameters. This choice has to be confirmed using energetic analysis on real road profile.

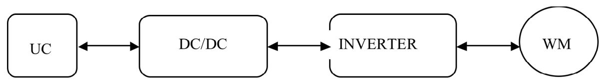

Fig. 3 Energy flow between UC and electric motor during deceleration (from right to left) and acceleration (from left to right)

TABLE I
CALCULATION OF IDEAL ULTRA-CAPACITOR TO RECOVER ENERGY OF 'PHEBUS' VEHICLE

Parameters	Traction	Recovery	Unit (SI)
Mass	1000	1000	Kg
$\eta_{DC/CD}$	97	97	%
η_{INV2}	97	97	%
η_{INV1}	97	97	%
P_{max}	6000	4890	Watt (W)
U_{scmax}	200	200	Volt (V)
Δt	10	10	Second (s)
E_{max}	60000	48900	Joule (J)
U_{scmin}	100	100	Volt (V)
I_{scmin}	30	24,45	Ampere (A)
I_{scmax}	60	48,9	Ampere (A)
I_{moy}	45	36,7	Ampere (A)
C_t	4,5	3,67	Farad (F)
Ns	74	74	-
Np	1	1	-
C_{cell}	333,3	271,4	Farad (F)

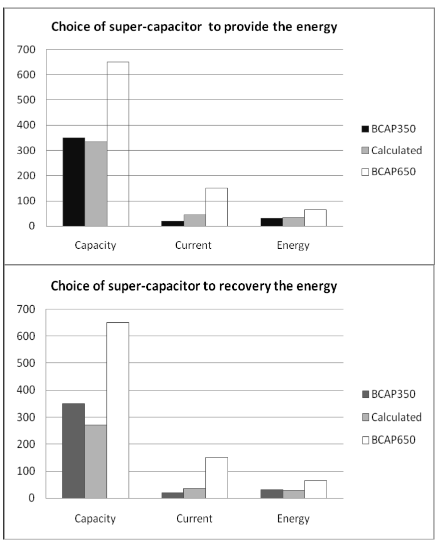

Fig. 4 Comparison between ideal sized UC and existing Maxwell components - Choice of ultra-capacitor between the components BCAP650 and BCAP350

B. Second approach: influence of driving profiles [3]

Based on a given standard profile (NEDC) and on the technical characteristics of 'PHEBUS' vehicle (given in the Table II), the energy developed and dissipated by the vehicle during this trip is calculated. This calculation requires a model of the vehicle dynamics including propulsion force and the various resistances. The calculation is based on following general equations:

- fundamental relation of dynamics

$$\sum \vec{F}_{ext} = m \cdot \vec{a} \tag{14}$$

- expression of mechanic power :

$$P(t) = F(t) \cdot v(t) \tag{15}$$

where $F(t)$ is the propulsion force and $v(t)$ is the vehicle speed;

- expression of needed energy:

$$E(t) = \int P(t) dt \tag{16}$$

To calculate F(t) we considered the dynamics of the vehicle. For basic HEV functionality and fuel consumption calculation, a simple longitudinal vehicle model is enough. The forces acting on the vehicle are :

$$\vec{F}_{ext} = \vec{F}_R + \vec{F} \tag{17}$$

where $\overrightarrow{F_R}$ is the total resistance force on the vehicle and it's equal :

$$\vec{F}_R = \vec{F}_{RR} + \vec{F}_A + \vec{F}_P \tag{18}$$

where :

$$F_{RR} = m \cdot g \cdot C_r \tag{19}$$

is the rolling resistance

$$F_A = \frac{1}{2} \cdot \rho_{air} \cdot S \cdot C_d \cdot v^2 \tag{20}$$

is the wind resistance (aerodynamic drag)

$$F_P = m \cdot g \cdot \sin(\alpha) \tag{21}$$

is the grade resistance (gravity)

And finally, with (14) we can be calculated the force F(t) :

$$m\frac{dv}{dt} = F(t) - mgC_r - mg\sin(\alpha) \cdots \cdots - \frac{1}{2}\rho_{air} S C_d v^2(t) \tag{22}$$

Figure 5 gives respectively the evolution of vehicle speed (a), propulsion force (b), vehicle mechanical power (c) and resulting energy (c) during NEDC profile. According to those curves, the sizing characteristics of the ultra-capacitors are summarized in the Table III for each road slope. We cans see in this table the minimum and maximum values of energy in the ultra-capacitors.

TABLE II

TECHNICAL SPECIFICATIONS OF THE 'PHEBUS' VEHICLE

Specifications of vehicle		
Parameters	**Value**	**Unit**
Mass	1000	Kg
Acceleration time	10	sec
Maximal speed	65	Km/h
Rolling resistance coefficient	0,00904	-
Engine power maximal	6	Kw
Voltage maximal of electrical system	200	V

TABLE III

UC SIZING CHARACTERISTICS FOR VARIOUS WORKINGS

Slope (%)	**0**	**3**	**5**
Force max (N)	1150,68	1444,84	1640,82
Force min (N)	-855,48	-561,31	-365,33
Power max (W)	11917,37	17261,38	20821,68
Power min (W)	-6008,44	-3646,94	-2078,19
Energy max (J)	9986756,83	14465039,99	17448571,78
Energy min (J)	-4590449,63	-2786264,97	-1589819,03
Slope (%)	**8**	**10**	
Force max (N)	1934,40	2129,74	
Force min (N)	-71,75	123,59	
Power max (W)	26155,01	29703,74	
Power min (W)	-80,02	0	
Energy max (J)	21917900,69	24891736,08	
Energy min (J)	-54336,45	0	

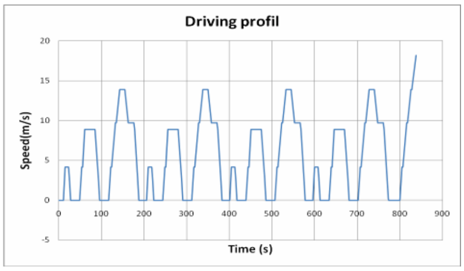

Fig. 5a Evolution of vehicle speed during NEDC profile

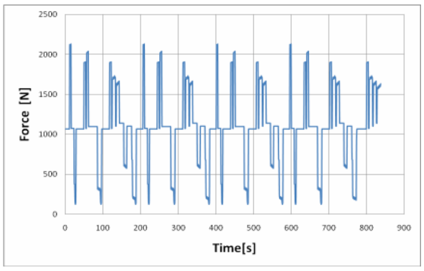

Fig. 5b Evolution of propulsion force during NEDC Profile

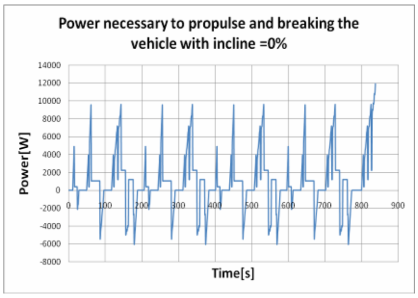

Fig. 5c Evolution of power during NEDC profile

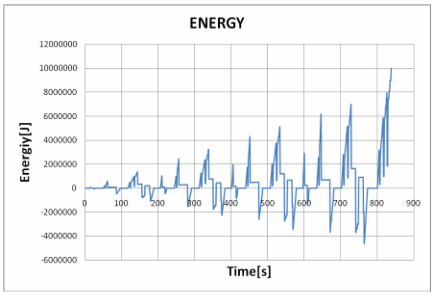

Fig. 5d Evolution of energy during NEDC profile

In the profil shown in Fig. 5.a, we can see three phases:

- acceleration phase, when the speed increases,
- constant speed phase,
- deceleration phase, the speed dicreases.

In Fig. 5.b, the prolusion force can be negative or positive:

- the positive force correspond to a propulsion of the vehicle and in this case the UCs act as generator,
- and the in the case where the force is negative, energy is recovered in the UCs.

In conclusion, the choice of **BMOD0058 E015 A01-B1** is confirmed for the application to the vehicle 'PHEBUS'.

III. *EXPERIMENTAL TESTS OF ULTRA-CAPACITORS*

A. Goals of the tests

After the sizing of ultra-capacitors for vehicle 'PHEBUS', the components have been tested to determine their real electrical parameters and also to evaluate their real energetic behaviour (efficiency during consecutive charges and discharges). Influence of temperature has been investigated too.

B. Electrical tests at room temperature [4]

The first tests aim to determine the internal resistance R_s and the capacity C_s of ultra-capacitors (see electrical model presented in Figure 6) at room temperature of around 20°C. To achieve these measurements, charges and discharges at constant current I are realized as shown in Figure 7.

Then the resistance R_s is computed with

$$R_s = \Delta U_3 / I \qquad (23)$$

where ΔU_3 is the voltage drop obtained from the intersection of the auxiliary line (tangent of the discharge curve) and the time base at the start of the discharge (see Figure 7). The capacity C_s is computed with

$$C_s = I \cdot \Delta t / \Delta U \qquad (24)$$

where $\Delta U = U_1 - U_2$ and $\Delta t = t_1 - t_2$ the voltage U_1 corresponds to 80% of the maximal voltage obtained at t_1 and U_2 corresponds to 40% of the maximal voltage obtained at t_2.

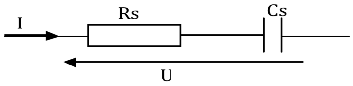

Fig. 6 Electrical model of ultra-capacitors[5]

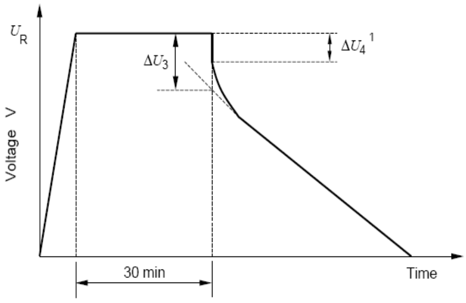

Fig. 7 Evolution of voltage during charge and discharge

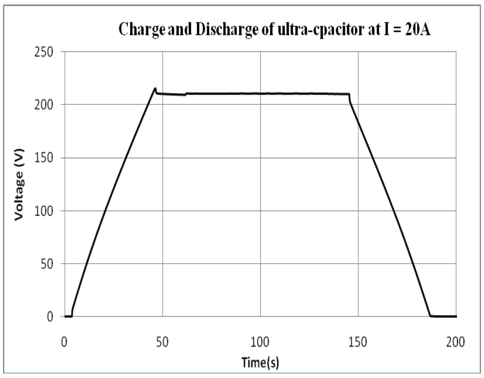

Fig. 8a Result of the evolution of voltage during the charge and discharge

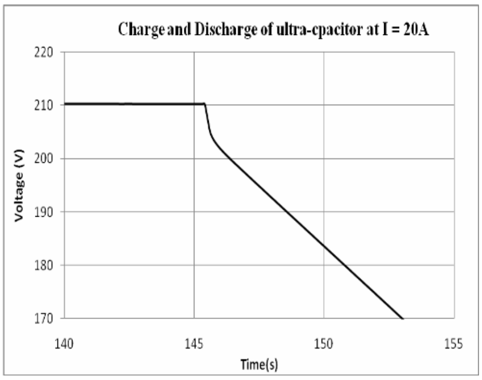

Figure 8b : Zoom on the figure 8a when the discharge begins

Figures 8a and 8b give test results obtained with the complete pack. In figure 8a, the evolution of voltage have three steps. Firstly the voltage increases from 0 to 210V, corresponding to the charge of the capacitors. Secondly, the voltage is kept constant and thirdly the voltage decreases from 210V, corresponding to the discharge of the capacitors. Table IV and V give the values of ultra-capacitors experimental characteristics respectively for the complete pack (14 modules of 6 capacitors) and for one module of 6 capacitors. Finally, Table VI gives a comparison between the vendor values and the measured ones, showing a remarkable good agreement. The datasheet gives 58 F for the capacitance and 0,019 Ω for the resistance, whereas the tests give in middle 64 F for the capacitance and 0,017 Ω for the resistance

TABLE IV

VALUES OF CAPACITORS ELECTRICAL PARAMETERS FOR THE COMPLETE PACK

PACK : Usc = 210V / C = 4,14F / R = 0,266Ω / E = 91287J (W/s)							
Test at	MEASURES and CALCULATION						
	U_{max} (V)	I_{max}(A)	ΔU(V)	R_{Imes}(Ω)	U_1-U_2(V)	t_2 - t_1(s)	C_{Imes}(F)
I= 5A - U=210V	210,65	5,721	1,37	0,24	84,29	71,49	4,85
I= 10A - U=210V	210,42	10,91	2,88	0,26	84,27	36,1	4,67
I= 15A - U=210V	210,59	16,20	4,37	0,27	84,43	24,05	4,61
I= 20A - U=210V	210,64	21,33	5,36	0,25	84,33	18,3	4,63

TABLE V

VALUES OF CAPACITORS ELECTRICAL PARAMETERS FOR THE PACK

MODULE 12 : Umax = 15V / C = 58F / R = 0,019Ω / E = 6525J (W/s)							
ESSAI à	MESURES ET CALCULS						
	U_{max} (V)	I_{max}(A)	ΔU(V)	R_{Imes}(Ω)	U_1-U_2(V)	t_2 - t_1(s)	C_{Imes}(F)
I= 5A - U=15V	15,16	5,759	0,097	0,017	6,081	72,05	68,235
I= 10A - U=15V	15,16	10,92	0,193	0,018	6,061	36,2	65,197
I= 15A - U=15V	15,11	16,07	0,257	0,016	6,058	24,2	64,187
I= 20A - U=15V	15,04	21,17	0,4	0,019	5,947	17,9	63,726

TABLE VI

COMPARISON BETWEEN CONSTRUCTOR AND MEASURED VALUES OF UC ELECTRICAL PARAMETERS

Parameters	C_s ***(F)***	R_s ***(mΩ)***
Constructor value	58	19
Experimental value	64,4	17,5
Relative differences	+11%	-7.9%

C. Efficiency of UC charges and discharges at room temperature

The procedure to calculate the efficiency during consecutive charge and discharge is the following. One ultra-capacitor is charged with a constant current, from the voltage *Umin* to the voltage *Umax*. During the charge the voltage *v(t)* and the current *i(t)* are measured. The power can be calculated with

$$P_C(t) = v(t) \cdot i(t) \tag{25}$$

and the energy with

$$E_C = \int P(t) \cdot dt \tag{26}$$

At the end of the charge (*u* = *Umax*), the value of the energy that is stored in the ultra-capacitor during the charge is known.

The ultra-capacitor is discharged with the same current than the one used for the charge. As for the charge, the measurements of the voltage and the current makes it possible to compute the power and the discharge Energy E_D. The end of discharge is obtained when the voltage *u* exactly equals *Umin*.

Then the efficiency is

$$\eta = E_D / E_C \tag{27}$$

TABLE VII

VALUES OF POWER, ENERGY AND EFFICIENCY FOR ONE UC MODULE FOR A CHARGE FROM 1V TO 15V AND A DISCHARGE FORM 15 TO 1V

MODULE 7 : Umax = 15V / C = 58F / R = 0,019Ω / E = 6525J (W/s)									
	CHARGE de 1 à 15V								
Test	MEASURES								
at	U_{min} (V)	U_{max} (V)	I_{min}(A)	I_{max}(A)	P_{min}(W)	P_{max}(W)	E_{min}(J)	E_{max}(J)	E_{CH}(J)
I= 5A - U=210V	1,00183	15,007	5,146	5,2168	5,1833	77,8981	24,16	7031,1	7006,9
I= 10A - U=210V	1,01703	15,012	10,34	10,382	10,544	155,58	24,19	7065,1	7040,9
I= 15A - U=210V	1,01773	15,01	15,63	15,673	15,937	234,878	23,47	7040,2	7016,7
I= 20A - U=210V	1,03207	15,002	20,81	20,842	21,497	312,518	22,82	6949,8	6927
DISCHARGE de 15V à 1									
Test	MEASURES								
at	U_{max} (V)	U_{min} (V)	I_{max}(A)	I_{min}(A)	P_{max}(W)	P_{min}(W)	E_{min}(J)	E_{max}(J)	E_{dCH}(J)
I= -5A - U=210V	1,00702	15,075	-5,208	-5,166	-78,13	-5,2147	-6849	-6,688	6842,7
I= -10A - U=210V	1,01553	15,083	-10,34	0,0857	-153,5	1,29618	-6748	3,0982	6751,3
I= -15A - U=210V	1,00836	15,004	-15,55	-5,512	-229,6	-15,647	-6659	4,4003	6663,8
I= -20A - U=210V	1,00065	15,102	-20,83	0,1903	-304,6	2,87846	-6542	6,8561	6549,2
Efficiency									
						η_5	η_{10}	η_{15}	η_{20}
						0,97656	0,959	0,9497	0,9455

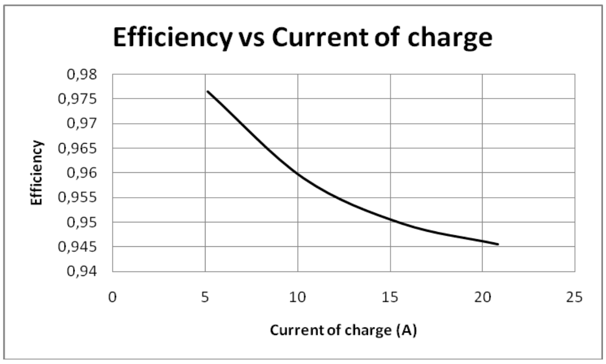

Fig. 9 Evolution of the efficiency versus the current of charge (one UC Module for a charge from 1V to 15V and a discharge form 15V to 1V)

TABLE VIII

VALUES OF POWER, ENERGY AND EFFICIENCY FOR the complete pack for a charge from 110V to 210V and a discharge form 210V to 110V

PACK : Umax = 210V / C = 4,14F / R = 0,266Ω / E = 91287J (W/s)									
	CHARGE de 110V à 210V								
Test	MEASURES								
at	U_{min} (V)	U_{max} (V)	I_{min}(A)	I_{max}(A)	P_{min}(W)	P_{max}(W)	E_{min}(J)	E_{max}(J)	E_{CH}(J)
I= 5A - U=210V	109,888	210,78	3,36564	4,8661	507,111	1159,26	22797,11	97715,4	74918
I= 10A - U=210V	109,941	210,26	8,82406	10,112	1075,28	2279,05	22961,27	96320,7	73359
I= 15A - U=210V	109,903	210,08	13,9468	15,204	1581,1	3166,36	23978,28	96511,5	72533
I= 20A - U=210V	109,974	210,39	16,8258	20,321	2084,4	4292,8	23430,51	95570,6	72140
DISCHARGE de 210V to 110V									
Test	MEASURES								
at	U_{max} (V)	U_{min} (V)	I_{max}(A)	I_{min}(A)	P_{max}(W)	P_{min}(W)	E_{min}(J)	E_{max}(J)	E_{dCH}(J)
I= -5A - U=210V	110,79	210,21	-0,4898	-5,832	-102,96	-1214,94	-77137,4	-4414,93	72723
I= -10A - U=210V	110,983	209,07	-5,7686	-10,975	-1199,3	-2278,5	-72618,6	-1495,48	71123
I= -15A - U=210V	110,868	210	-0,2969	-16,161	-62,345	-3324,13	-70038,8	-485,97	69553
I= -20A - U=210V	110,763	209,06	-2,0704	-21,128	-424,24	-4318,81	-68177,3	-1222,75	66955
Efficiency									
						η_5	η_{10}	η_{15}	η_{20}
						0,97069	0,969515	0,95891	0,9281

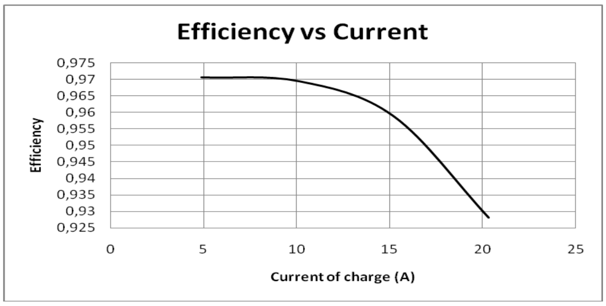

Fig. 10 Evolution of the efficiency versus the current of charge (complete pack for a charge from 110V to 210V and a discharge form 210V to 110V)

The Table VII gives the values of power, energy and efficiency during a charge/discharge of one pack between 1 V and 15 V. The evolution of the efficiency with the current of charge/discharge is given in the Fig. 9 for one module. Comparable results are given in Table VIII and Fig. 10 for a complete pack.

The following conclusions can be made:

- the mean stored energy in each module is around 7kJ for charge/discharge between 1V and 15V,
- the mean stored energy in the complete pack is around 72 KJ for a charge discharge between $U_{max}/2 \approx 110\,V$ and $U_{max} \approx 210\,V$ (this type of charge/discharge being classically used in real system),
- as expected, the efficiency decreases with the current intensity, but, for the complete pack, even for a large current of 20 A (corresponding to a power up to 4,5 kW), the efficiency is higher than 92%.

D. Influence of temperature on the UC characteristics [6]

For the moment, FEMTO-ST Institute is working on the experimental characterization of the influence temperature on the previously designed UC pack for the vehicle 'PHEBUS'. Those tests are realized in climatic chamber by controlling working temperature from -30°C to 60°C (see Fig. 11a and 11b). Preliminary results are presented in this paragraph.

Fig. 11a Photography of the UC complete pack designed for 'PHEBUS' vehicle

Fig. 11b Test of UC complete pack the climatic room at FEMTO-ST Institute

The protocol of this test is the following: the room (and UC) temperature is maintained during four hours. After this time we can begin the tests (charge and discharge for the UC at different currents). The table IX represents the results of capacitance and resistance calculations regarding the pack at a temperature of –30°C.

TABLE IX
VALUES OF RESISTANCE, AND CAPACITANCE FOR THE COMPLETE PACK

PACK : Umax = 210V / C = 4,14F / R = 0,266Ω / E = 91287J (W/s)								
	R(Ω)				C(F)			
TEMP (°C)	I=5A	I=10A	I=15A	I=20A	I=5A	I=10A	I=15A	I=20A
60	0,25	0,26	0,24	0,25	4,56	4,43	4,52	4,53
40	0,29	0,26	0,27	0,26	4,59	4,46	4,43	4,35
30	0,31	0,27	0,27	0,27	4,51	4,45	4,4	4,37
10	0,33	0,28	0,3	0,31	4,63	4,47	4,49	4,4
0	0,33	0,3	0,32	0,33	4,99	4,5	4,47	4,44
-10	0,34	0,34	0,34	0,35	4,67	4,37	4,47	4,45
-20	0,42	0,39	0,39	0,39	4,55	4,52	4,52	4,49
-30	0,46	0,44	0,43	0,5	4,48	4,54	4,54	4,51

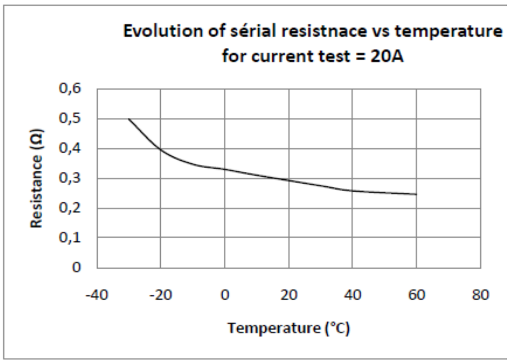

Fig. 12 Evolution of the serial resistance with the UC temperature

TABLE X
VALUES OF EFFICIENCY FOR DIFFENRENT TEMPERATURE, the complete pack for a charge from 110V to 210V and a discharge form 210V to 110V

	Efficiency			
TEMP (°C)	I=5A	I=10A	I=15A	I=20A
60	0,985	0,972	0,957	0,907
40	0,972	0,961	0,947	0,889
30	0,963	0,951	0,943	0,923
10	0,989	0,969	0,905	0,905
0	0,977	0,971	0,939	0,902
-10	0,939	0,937	0,880	0,874
-20	0,958	0,944	0,927	0,851
-30	0,976	0,968	0,940	0,898

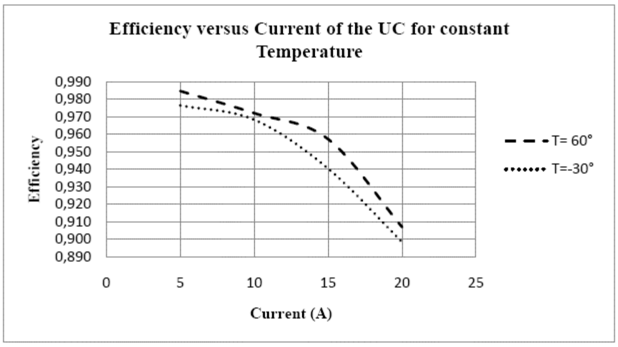

Fig. 13 Evolution of the efficiency versus the temperature at constant current (complete pack for a charge from 110V to 210V and a discharge form 210V to 110V)

We note that the serial resistance increases when the temperature decreases (as confirmed with the curve shown in Fig. 12): at 40°C, the resistance is approximately twice larger than the value given by the datasheet at 20°C. The consequence is that the voltage drop is more important when the temperature is lower. As a consequence the efficiency will increase with the temperature as shown in Table X and Fig. 13. However, the efficiency of the pack will be higher than 90% whatever the charge/discharge current or the temperature.

Concerning the capacitance, it is more difficult to conclude, as it is explained also in [6]. The evolution shown in the Table IX is not clear, but we can see that the relative variations of the UC pack capacitance are relatively limited. In a first order approach, we can consider that the capacitance does not depend on temperature. Then, even if the stored energy will not vary a lot with temperature, the variations of serial resistance will have a consequence on the evolution of the constant time: the charge/discharge time will increase when the temperature deacreases.

IV. CONCLUSION

In this paper, the authors have described the following points:

- the methodology of sizing method for an ultra-capacitor energy storage system;
- the application of this methodology to an original small hybrid electric vehicle PHEBUS (a pack of 4,14F/210V has been designed);
- the choice of a ultra-capacitors pack of Maxwell Company to realize the energy storage system;
- and finally the experimental tests showing firstly a good agreement between the vendor characteristics and the measurement results and secondly an efficiency of charge/discharge always higher than 90% whatever the current of charge/discharge (within the range 0A to 20A) and the temperature (within the range -30°C to 60°C).

The next works will concern firstly the determination of thermal resistance and capacity to design the cooling system of the UC complete pack and secondly the tests of charge/discharge considering NEDC profile.

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