Design of a Supercapacitor-Battery Storage System for a Waste Collection Vehicle

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***Abstract*—This paper deals with the design of battery-supercapacitors energy storage for an electric waste collection vehicle. The vehicle was simulated on an urban driving cycle and a simple power flow management based on the power limitation in battery was developed. The main benefit of the hybridization, the reduction of the losses within the battery, is outlined and we show how the ultracapacitor pack could be designed in order to prevent stress on battery and, consequently, to extend its lifetime.**

Keywords–Hybrid electric vehicle, battery-supercapacitors hybrids, driving cycle, power management.

I. Introduction

Despite the efforts of the French government to stimulate the market by subsidising 20% of the cost overrun of a "green" vehicle in comparison to a conventional internal combustion vehicle (ICEV), only a small number of waste collection vehicles are hybrid or electrical vehicles [22]. The hybrid WCV has low emissions and the fuel consumption is at least 20% less than an ICEV – with regard to serial or parallel hybrids, but less if we consider gasoline vehicles with start/stop mechanism [1]. Electrical WCV is silent with no gas emission and without fuel consumption. In spite of these advantages, the price and the limited driving ranges are the true drawbacks of electrical WCV. The hybridization is a solution to these problems because the internal combustion engine is cheaper today than an electric powertrain and he offers a great autonomy [2]. Another solution could be the increase of the battery lifetime, which is the most expensive cost of an electrical vehicle [3]. This could be a really good mid term solution especially for WCV – powered exclusively by low cost batteries as lead-acid – as long as the lead-acid battery will dominate the market [4].

This paper focuses on a hybrid source for electrical WCV intended to increase the lifetime of the battery. The hybrid source is made of supercapacitors (SC) connected via a power converter in parallel to the high voltage battery (Fig. 1). The association of supercapacitors to battery or fuel cell was analyzed extensively in literature whereas the lifetime extension was rarely mentioned [5], [10], [11]. Usually the hybrid source is used for power assistance in fuel cell systems, hybrid vehicles, diesel-electric engines, or as energy buffer with higher efficiency than a pure battery [12]-[16]. In this paper, we propose a simple power flow management which is intended to reduce the battery stress by limiting the battery current [18] and an original method for supercapacitor pack sizing. Vehicle modelling and simulation assumptions are developed in the next section. Storage system sizing and the influence of some parameters are discussed in the last section.

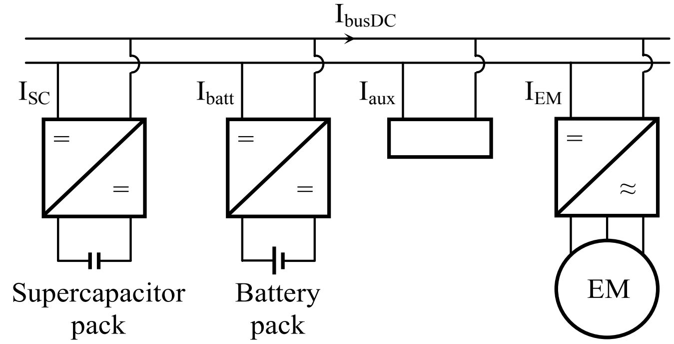

Figure 1. A schematic of the hybrid storage system and drive train

II. Simulation Hypothesis

VCW was modelled and simulated under VEHLIB. VEHLIB, developed by INRETS, is a simulation environment based on Matlab/Simulink. Road (ICEV, hybrid and electrical) and railway vehicles can be simulated for different driving cycles. Components models and simulation method are exhaustively described in [6]. In this section, we briefly summarize models parameters and simulation assumptions.

A. Vehicle Simulation

The vehicle chassis and dimensions are the same than the PVI Puncher, a waste collection electrical vehicle of 20t Authorised Gross Vehicle Weight (5t chassis and 5t lead-acid battery). Details on vehicle, wheels, dimensions, weight and transmission are given in Table I. The rolling force is considered constant (100N/t), aerodynamic and gravity forces are took into account in the resistance force, F_{road}:

$$F_{traction} - F_{road} = M \frac{dv}{dt} \quad (1)$$

Where M is the vehicle mass and v is the linear speed of the vehicle. The max speed is limited by the transmission at 45km/h in collection phase.

Other assumptions are:

- Electric motors and its associated static converters have an overall efficiency of 92.5%, 100% respectively. The motor maximum power is 90kW. The transmission and gearbox has an overall efficiency of 95%.
- The compaction phases come from ARTEMIS driving cycle, but the necessary power is unknown. We have made the assumption that a maximum power of 10kW is demanded for each compaction instance and this power covered the necessary mean power of other auxiliaries like heating, air conditioning system…
- We assumed a full recovered braking energy. This factor is very important for the energy storage design.
- The battery is modelled using a Thevenin equivalent circuit made of an open circuit voltage in series with an internal resistance. The value of each of them depends on the state of charge.
- The supercapacitor model is based on a capacitor in series with a resistor, which is the sum of all internal resistance, and in series with a parallel RC cell.

TABLE I. VEHICLE CHARACTERISTICS

Elements	Physical quantity	Values
Motor	Power rating	50kW (90kW$_{max}$)
	Maximum torque	330 Nm
	Rotational speed	1500 min^{-1}
	Nominal voltage	3 x 400Vac (50Hz)
	Nominal current	100A
	Efficiency	92,5%
	Mass	580kg
Battery	Open circuit voltage	528V
	Rated capacity	260Ah
	Internal resistance	88mΩ
	Mass	2.5t
SC pack	Voltage (max/min)	540V / 270V
	Capacity	10F
	Internal resistance	70mΩ
	Mass	100kg
Gear	Ratio	5.96
	Efficiency	95%
Vehicle	Wheels	56cm (radius)
	Mass	15t
	dimensions	2.3m x 3.8m x 8.7m
	Front area	6.44m²
	Dragging coefficient	0.6
	Rolling resistance	100N/t

B. *Driving Cycle*

Energy storage is designed on a specific driving cycle named ARTEMIS. Using the principles and methods developed for a conventional car, a representative driving cycle has been built-up for an ICE waste collection vehicle [17]. Data has been recorded in 1990 during a week, in Grenoble (France), when a Renault IV GR191 was instrumented and monitored in normal operation. This cycle includes a liaison trip, and a collect phase. The main characteristics of the cycle are summarized in Table II.

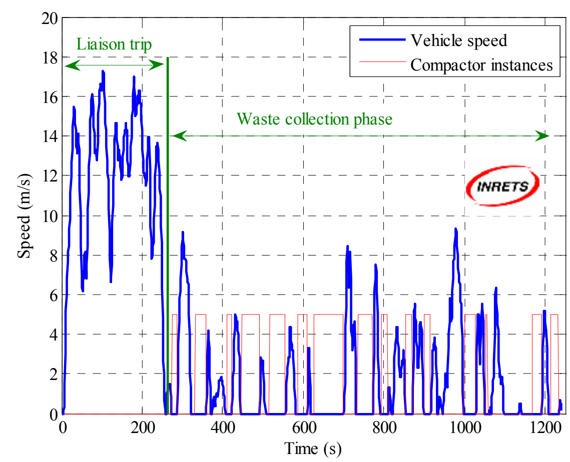

Figure 2. ARTEMIS driving cycle and the two phases: liaison trip and collection phase

TABLE II. ARTEMIS DRIVING CYCLE CHARACTERISTICS

	Approach phase	Waste collection phase	Entire cycle
Average speed [m/s]	10.6	1.4	3.41
Maximal speed [m/s]	17.3	9.3	17.3
Distance [km]	2.9	1.3	4.2
Time	4min31s	16min11s	20min42s
Acceleration (min/max)	1.3 m/s^2 to -2.1 m/s^2		

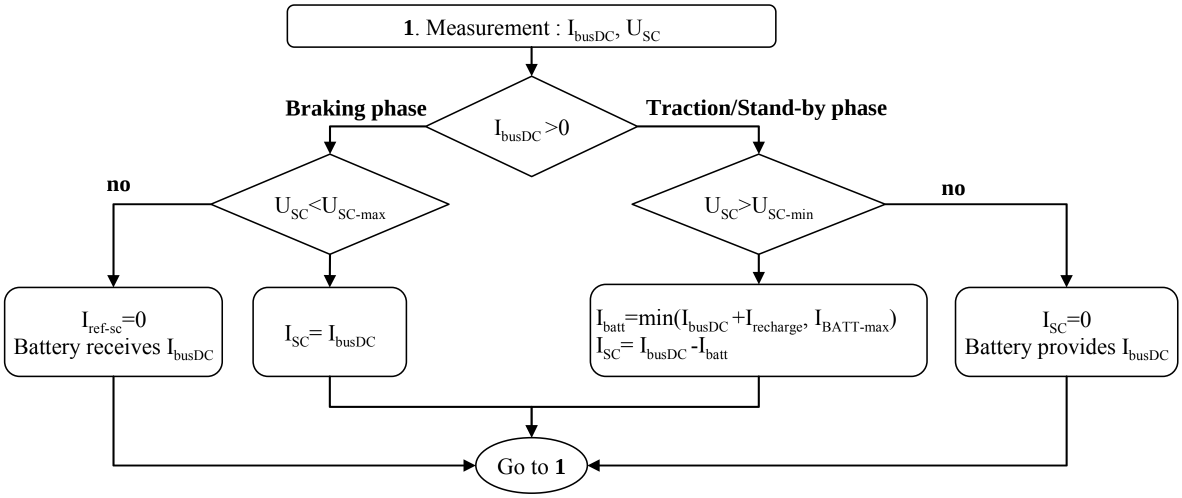

Figure 3. Flowchart showing the control strategy for a requested load current from energy storage system

C. *Power Flow Management*

There is no standard solution to the problem of optimal power sharing between two sources. The aim of a power sharing strategy is to get the best of each source. There are three mains strategies to share the power between batteries and supercapacitors:

- Heuristic algorithms are based on basic principles and general specifications of the system. The main advantage is that we do not need information about the driving cycle. This kind of algorithm is easier to implant than others algorithms [9], [19].
- Deterministic algorithms are based on analytical minimization of losses. The driving cycle and detailed information about the vehicle allows optimizing operation points [20].
- Non-deterministic algorithms are finding themselves an operation point. There are some mathematical methods such as stochastic methods, fuzzy logic and/or neural networks, which find themselves this optimal point [8], [21].

In this paper, we propose a simple power flow management, a heuristic algorithm, based on battery current clipping (Figure 3). The goal of this strategy is to reduce the battery current stress, and we hope to improve the energy storage efficiency and extend the life of the batteries [7], [19]. The gauge is the *rms* current.

During the traction phase, the battery current is limited to a constant, maximal, value ($I_{BATT-max}$). Any remaining current is supplied by the supercapacitors. If the request for current cannot be supplied by the supercapacitors, which could be empty, then the remainder is supplied by the batteries.

Finally, if power is delivered to the energy storage system due to regenerative braking, then this current is directed entirely to the supercapacitors up to the maximum voltage. If the supercapacitors are fully charged, additional current is directed to the batteries. Another way to charge the supercapacitors is to pump from battery. A PI controller keeps the supercapacitors voltage to a constant level (520V). This recharging way is forbidden in braking phase.

D. *Preliminary Sizing*

The preliminary sizing gives an $I_{BATT-max}$ current. The starting point is the power obtained from the ARTEMIS driving cycle. This power comes from the derivate of the vehicle speed for a given mass (15t). Assuming an ideal vehicle, an iterative loop tries to keep constant the energy of supercapacitors between the beginning and the end of the cycle. The goal of this loop is to decrease $I_{BATT-max}$ current while the supercapacitors are overcharged. The optimum $I_{BATT-max}$ is the maximum allowable current when the supercapacitors energy is the same between at the beginning and the end of the cycle.

The preliminary sizing algorithm gives an $I_{BATT-max}$ of 18A. Consequently, the necessary energy for 8hours (24cycles) is 34kWh and the maximum stored energy in supercapacitors is 173Wh. The drawbacks of this simple algorithm are the following: it cannot take into account the efficiencies, the recharging supercapacitors loop and it consider the entirely recovered energy. Nevertheless, it gives an initial value for $I_{BATT-max}$, for the supercapacitors capacity and the consumed energy.

E. *Simulation Results*

Simulation results are shown in Fig. 4 for a maximum allowable battery current $I_{BATT-max}$ of 18A and a 10F/540V SC pack. A zoom of the first 200s outlines the current sharing between SC and battery and also the SC recharging loop from battery (between 50s and 60s).

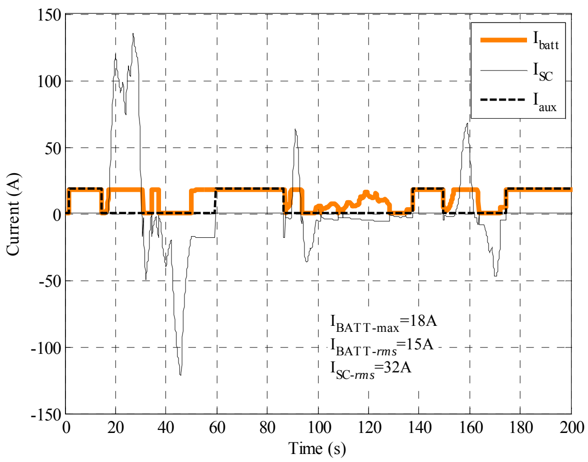

Figure 4. Currents over the first 200s of the collection phase of the ARTEMIS driving cycle. Currents are on the DC bus.

In the battery, the current is always between 0A and 18.5A and the *rms* current is lower, 15A. Without SC pack, the *rms* value of the battery current would be 40A, with extremes of -158A and 176A.

In the SC pack, the current varies between -207A and 200A and its *rms* value is 32A. The SC voltage varies between 540V and 300V.

As it could be expected, more simulations have been done, for different pack and $I_{BATT-max}$ in order to find the minimal *rms* current in batteries. These are developed in the next section.

III. Hybrid Storage System Design

As it could be seen in the previous section, there are many parameters that play a role in the storage system design: the volume and weight of SC and battery, the rated temperature, depth of discharge and projected battery lifetime, the quantity of the recovered energy …. There are also parameters related to the control strategy: the *rms* currents in battery and SC, the maximum admissible current in battery and the controlled voltage level of SC. In this section, we will focus on the last two and their influence on the *rms* currents in SC and battery. The SC and battery sizing result from this analyze and from energy reflections.

Firstly, simulations have been done for three different SC packs: 1.5F – 6F – 15F / 540V. The *rms* currents in battery and SC are shown in Fig. 5 and Fig. 6.

Maximum four zones could be outlined for each pack. For example, the first zone ranges from 0A to a maximum admissible current lower than 13A, for the 15F pack. The characteristic of this zone is that SC voltage drops frequently below 50% of maximum and the battery has to provide the reminder. Consequently, current spikes increase the *rms* value of the battery current.

In the second zone, the SC pack is never completely depleted or full. Thus, the battery current is always less than or equal to $I_{BATT-max}$.

In the third zone SC are sometimes fully charged and, as a result, the battery is recharged, negative spikes modifying the *rms* value of the battery current.

SC are not used in the forth zone. The storage system is represented solely by the battery. Table III shows that the four zones do not always exist.

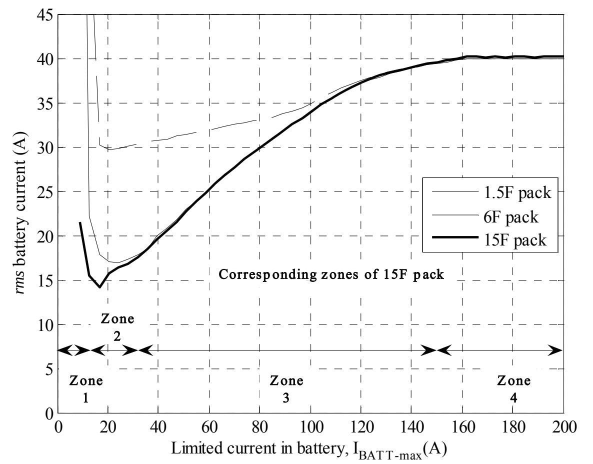

Figure 5. *rms* battery current in function of $I_{BATT-max}$, for 3 SC packs

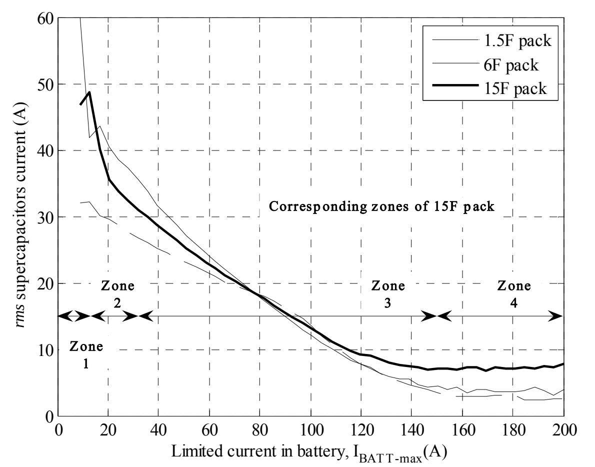

Figure 6. *rms* SC current in function of $I_{BATT-max}$, for 3 SC packs

TABLE III. Behaviour Zones for Different SC Packs and $I_{BATT-MAX}$

SC pack	Zone 1	Zone 2	Zone 3	Zone 4
1.5 F	$I_{BATT-max}$ = 0 ... 100A	-	100... 150A	150 ... 200A
3 F	0 ... 70A	-	70 ... 150A	
6 F	0 ... 30A	-	30 ... 150A	
10 F	0 ... 17A	17 ... 28A	28 ... 150A	
15 F	0 ... 13A	13 ... 32A	32 ... 150A	
25 F	0 ... 9A	9 ... 36A	36 ... 150A	

An optimal design for the SC pack should make it works in zone 2. Nevertheless, the battery *rms* current could be strongly reduced by using SC even if a zone 2 does not exist. For example, the 6F pack divide by 2 the *rms* current in the battery ($I_{BAT-max}$=25A) when the working zone is 1 or 3.

The consequences of the $I_{BATT-max}$ on the SC *rms* current are shown in Fig. 6. It can be seen that the *rms* value decrease when $I_{BATT-max}$ increased. It is important to verify the *rms* value does not exceed a maximum of about 100A. In our application the *rms* value of 32A doesn't stress at all the SC.

The influence of the SC voltage level on the battery lifetime is not so obvious. In fact, maintaining a constant level of the SC voltage influence the quantity of available energy to be transferred to and from the load. This quantity could force the battery to deliver more or less power. An optimum range for the SC voltage must exist. E.g. the optimum voltage of the 15F pack, assuming $I_{BATT-max}$ of 30A, range from 380V to 520V. Fig. 7 shows that the SC voltage has to be maintained at a high level, not only to improve the efficiency of the transferred energy, but also to reduce the *rms* current in battery.

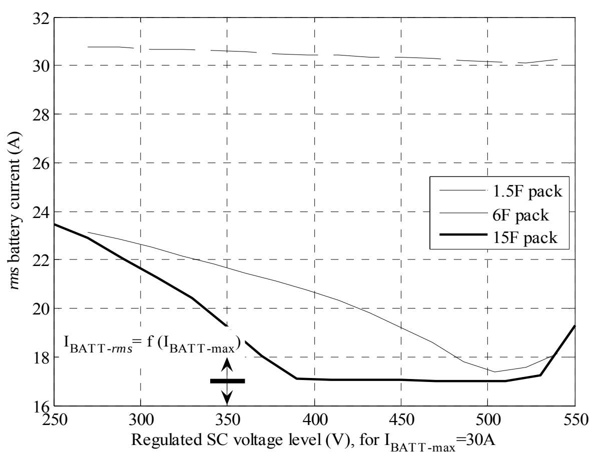

Figure 7. *rms* battery current in function of SC voltage, for 3 SC packs

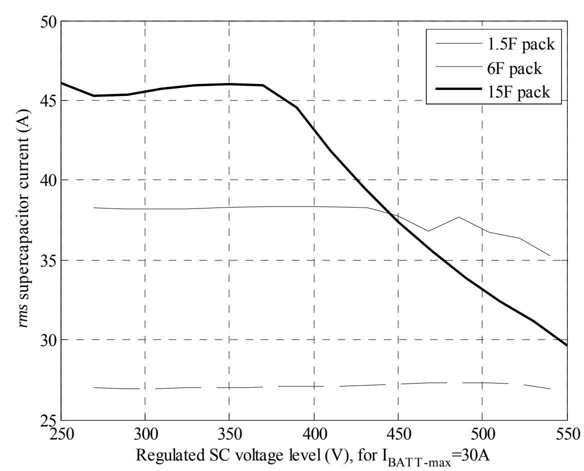

Figure 8. *rms* supercapacitors current in function of SC voltage, for 3 SC packs

TABLE IV. BATTERY SIZE FOR DIFFERENT RECOVERED ENERGY RATIO

Recovered energy/cycle (MJ)	Battery provided energy (MJ)	Battery mass (t)	Battery volume (m^3)
2.9 (100%)	156	2.4	1
1.5 (50%)	188	2.9	1.22
0.6 (20%)	204	3.2	1.33

Studying the influence of $I_{BATT-max}$ and SC voltage level is important in order to design the SC pack, to choose the right capacity as a function of *rms* value of the battery current, the available volume and maximum allowable weight onboard. Once the SC pack is choosen, the battery capacity could be defined as a function of the necessary energy on board but also as a function of the reminder power after SC action.

To design the battery capacity, some assumptions have to be made concerning the recovered energy and the battery lifetime. The last one is closely related to the vehicle daily duty and the recharging strategy.

An 8hours (24 ARTEMIS driving cycles) daily duty should discharge no more than 35% of the NPL130-6I (from Yuasa) battery capacity in order to allow 700 charge-discharge cycles at 20-25°C. Table IV shows the daily energy to be provided by the battery and outline the importance of the recovered energy on the battery size. These figures should be increased by 10% to take into account the temperature effect on the battery capacity.

CONCLUSIONS

This paper addresses the design of a battery-supercapacitors energy storage for an electric waste collection vehicle. The vehicle simulation shows the influence of different parameters on the battery current and how to design the supercapacitors pack in order to decrease the *rms* battery current. Simulations are based on a simple power flow management (the battery current clipping) and a typical urban driving cycle (ARTEMIS).

Future work, based on a more detailed battery model, will try to investigate the relationship between the *rms* current and the battery lifetime. An experimental setup will start cycling the energy storage under the current profile this autumn.

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