High power Lithium batteries usage in hybrid vehicles

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Abstract— **Hybrid vehicles require an energy storage device capable of delivering or absorbing high specific powers (powers per unit of the device size), and still, in some cases, adequate levels of specific energy.**
The paper shows that high power Lithium Batteries already on the market are able to fulfil this task satisfactorily, by means of experimental tests, whose results are shown and discussed.
The results show that very high power lithium batteries can be used in hybrid vehicles as the sole energy storage device, thus avoiding the complexity of composite (e.g. battery plus supercapacitor) storage systems.

Keywords- battery, lithium, hybrid electric vehicle

I. INTRODUCTION

The operation of storage batteries in hybrid electric vehicles requires to deliver and absorb large currents in short intervals of time, typically a few seconds or tens of seconds: the common judgment is that a lithium battery alone cannot provide high power density and energy density at the same time. Because of this, in some case "composite" or "hybrid" storage systems formed by power-oriented super-capacitors and energy-oriented batteries are considered (e.g. in [7]).

However, there are today on the market lithium cells that show a well balanced mix of power and energy, so that the whole energy storage system can be based on them, without resorting to hybridisation with supercapacitors or other power-oriented storage means.

The main problem of using lithium batteries at high powers and currents is during charging, that occurs when the vehicle makes regenerative braking. Indeed, often manufacturers impose limits on the charging current that imply charging powers much smaller than discharging ones, therefore limiting the effectiveness of the whole storage system.

It is, however, questionable whether for the very short durations of a braking the same current limits apply that are imposed for full recharge from battery empty. The paper investigates mainly this issue, based on the assumption that the stress induced into the battery by charging and discharging currents are related to the temperature rise. This assumption is then validated by means of cycle-life experimental evaluation.

II. PERFORMANCE OF A HIGH POWER LITHIUM BATTERY UNDER HIGH POWER CHARGE AND DISCHARGE

A. The device under test

The battery under test is one of the lithium cells capable of the highest power on the market[1].

It is a battery composed by a single cell having a nominal, two-hour capacity of 7,2 Ah.

Performance data for this cell are available for full discharges to up to $15C_n$, while pulse discharges may be performed to up to $20C_n$, where C_n represents the nominal battery capacitance, reported in manufacture's datasheet, expressed in Ah.

From manufacturer's graphical documentation the numerical data reported in Table I can be inferred, (where the discharge regime is reported in ampere per nominal Ah of battery capacity) that confirms the definite vocation of this battery for high powers, since very little charge penalty occurs.

TAB. I: BATTERY PERFORMANCE UNDER CONSTANT CURRENT DISCHARGE

DISCHARGE REGIME I/Cn (A/Ah)	0,5	1,0	5,0	10	15
DELIVERED CHARGE (%)	102	98	97	96	96
Average voltage (V)	3,85	3,80	3,70	3,60	3,50

According to this table therefore a single cell, whose mass is 226 g, should be able to deliver (at $15C_n$ regime, for about 230 s) around 1673 W/kg, (or 1460 W/kg if a overhead of 13% for case and BMS - Battery Management System- is taken into account).

However it is not clear which is the maximum time this discharge regime can be maintained without battery damage, nor what it is the *charging* current limits, and not, finally, how many times charge/discharge cycles with very high currents can consecutively be applied.

Therefore a campaign of experimental tests was planned, to evaluate the battery performance in terms that are immediately usable for hybrid vehicle rechargeable energy storage sizing.

First of all a suitable set of significant stresses must be defined.

[1] Battery of the "Ultra High Power" family, 7,2 Ah, from [10].

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B. Stress definition

The stress to which the considered storage device is to be subjected should reproduce, in a schematic idealised way, the stresses that are encountered in hybrid vehicle drive trains. However, since they are composed by idealised parts (e.g. constant current charges/discharges and pauses), the results are useful for other applications as well.

The cycle to be used is a consequence of the objective of the lab tests, and therefore the following different cycles have been defined:

Type 1 - full charge cycling cycle, in which the battery is fully charged and fully discharged. This cycle gives information about the battery capability to absorb and deliver power in abstract, but it is not significant of actual hybrid vehicle battery stresses, in which shallow, high current, charges and discharges occur.

Type 2 - repeated partial charge cycle in which charge/discharge cycles are such that they can be repeated many times, without overcoming the battery over-temperature limits. This cycle implies shallow discharges and is more significant of actual battery operation onboard hybrid vehicles.

Type 3 - driving-cycle simulating battery cycle, in which the current to which the battery is subject is typical of hybrid vehicle usage operating in a NEDC driving cycle (New European Driving Cycle). This cycle gives additional information about real-life battery usage while, being much more complex, interpretation of the results are not easily transferred to other applications.

As common when electrochemical storage is involved, the basic charging and discharging phases are imposed to be constant current based, because this gives the clearest information on the storage performance, since electro-chemical reaction speed is directly related to the charge speed of evolution, i.e. to the current.

The full charge-cycling used is that of the type shown in fig. 1. It is constituted by a deep I-U charge followed by deep constant-I discharge up to the minimum cell voltage (here 2,8 V/cell). In the figure 1 a 10*C_n discharge current is considered, but other values have been used as shown below.

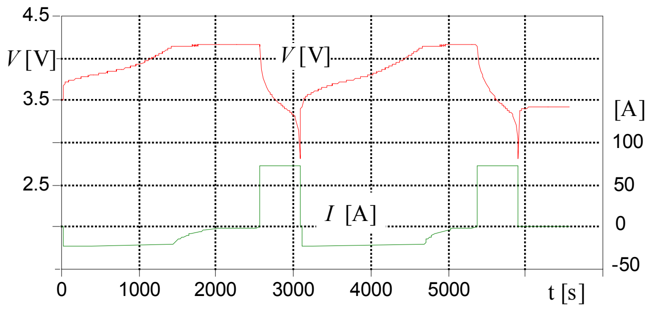

Fig. 1: Battery charge-discharge cycles using a discharge current of 10*C_n – voltage and current (positive during discharge).

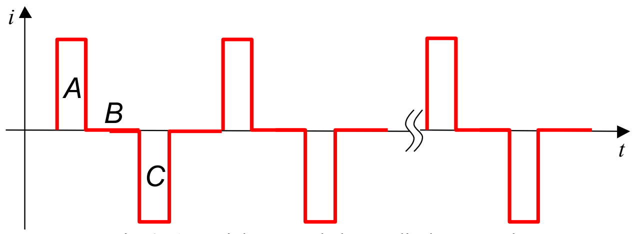

Fig. 2: A partial repeated charge-discharge cycle.

The repeated partial charge cycle is reported in fig. 2: it is constituted by constant-charge, constant-discharge and rest phases, with the following constraints:

- duration and current amplitude of charge phases ***A*** and discharge phases ***C*** are the same (so the cycle is charge-balanced). Values are chosen to maintain the lithium cell within the window voltage admitted (4,2-2,8 V).
- the phase ***B*** has a fixed duration of 20 s to simulate a typical vehicle battery rest.
- for each current amplitude and duration of phases ***A*** and ***C*** the battery temperature was measured.

This way the maximum charge/discharge current compatible with limits of voltage and thermal conditions is evaluated.

Finally tests of type 3 were introduced. It is well known that the NEDC cycle is composed by the four repetitions of the urban part, plus a suburban part [9]. The suburban part has normally a maximum speed of 120 km/h, but for low-powered vehicles, a version limited to 90 km/h may be used [9].

To define a battery current cycle based on low-powered NEDC, a series-hybrid drive train was considered, of the type shown in fig. 3. Based on a common battery management strategy [1, 6], in which the primary converter delivers the average power requested by the power train, while the battery delivers (or absorbs) the ripple around that average, this drive train was simulated and the corresponding battery current evaluated.

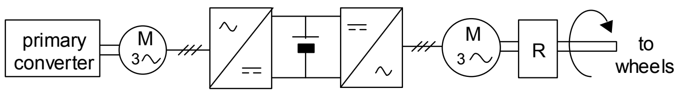

Fig.3: Simple SHEV drive train scheme.

The resulting current is shown in fig, 4, where the speed profile is shown as well; to make the plots clearer, only two (instead of four) urban parts of the cycle are displayed.

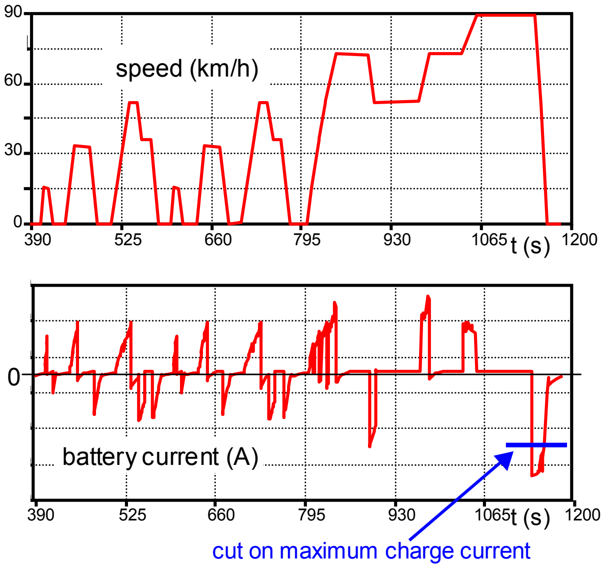

Fig. 4:NEDC cycle for lower –powered vehicles
(above, only two urban parts shown)
and corresponding battery current (below, simulated).

Since it is seen that the maximum battery stress occurs during the last vehicle braking action, is seems reasonable to give up part of the energy that could be recovered during the last brake, limiting the maximum charge to a value that allows the battery to be dimensioned with a symmetrical profile, i.e., with equal maximum charge and discharge current.

This to at least mitigate the battery difficulties with which charge currents.

As far as the actual maximum value of the peak currents, considering the results from type 2 tests, a value of I/C_n equal to 6 A/Ah is reasonable and has been chosen.

Type 3 tests were performed not only to evaluate battery performance, but also to estimate the battery cycle life, when subjected to this stress, i.e. to the typical hybrid vehicle stress.

C. *Basic results*

When subjecting the battery to cycles having the shape of fig. 1, charge and discharge powers are not constant.

To summarise in a compact way the results, however, it is useful to report the average powers. This was done for getting the results reported in Table III, (derived from one already published in [5]) in which the averaging was made during all discharge times, and during the constant current phase of the charging process (the constant voltage phases are of little interest for the case considered in this paper of hybrid vehicle storage systems, and averaging over them would alter significantly the meaningfulness of the results).

Moreover, in table III, the results are expressed also in terms of specific powers to make them more general. The end of charge condition was reaching the maximum allowed time when I/C_n was 20 A/Ah, or the minimum cell voltage in the other cases.

Tab. II: Battery powers during charge and discharge
(modules; mass includes case)

I_{dis}/C_n (A/Ah)	disch. duration (s)	I_{ch}/C_n (A/Ah)	P_{avg} (W)		P_1 (W/kg)	
			charge	disch	ch.	disch
20	5	3	85,8	546	330	2100
20	10	3	85,8	538	330	2070
20	20	3	85,8	528	330	2030
20	40	3	85,8	515	330	1980
20	60	3	85,8	496	330	1910
15	251	3	85,8	377	330	1450
10	512	3	85,8	254	330	976
5	992	3	85,8	135	330	518

The results of table III indicate a strong limitation in charging power due to the manufacturer's limit in the charge current.

It is however felt that this limit should actually apply only to full battery charge (where thermal problems may otherwise arise). In case of the hybrid vehicle, where short duration charge/discharge cycles occur, separated by pauses in which the battery current may stabilise, this limit can be overcome, given that the battery thermal behaviour is satisfactory.

Therefore tests of type 2 were performed as well, testing the battery at an ambient temperature of 23°C. A sample result related to a current of 6*Cn is reported in fig. 5, while the global set of results can be summarised as in table III. Although is clear from the in figure that the evolution of the refrigerating chamber temperature influences the battery case temperature, the difference becomes indeed constant after few charge-discharge cycles. The maximum case over-temperature registered, for charge-discharge current of 8*C_n and duration of 60 s, was about 7°C.

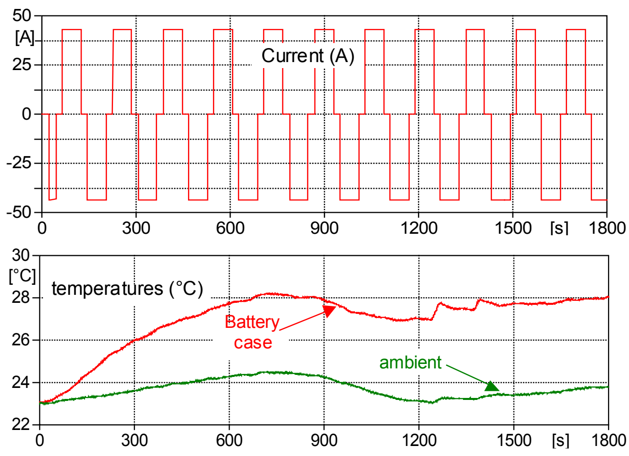

Fig. 5: Battery current and temperatures during a sample test of type 2.

Tab. III: Current, pulse duration and case over-temperature starting from ambient (23°C) in type 2 tests

I/C_n (A/Ah)	Pulse Duration (s)	measured stable case over-temperature (°C)
3	30	1,19
3	60	1,73
6	30	3,71
6	60	4,74
8	30	5,64
8	60	6,91
9	30	6,57

The main limitation for this kind of test is due to the maximum or minimum permissible lithium cell voltages, equal respectively to 4,2 V and 2,8 V: when the battery is near the full charge condition, pulse charges must be interrupted not to overcome the maximum allowable voltage. The opposite occurs when it is near to the full discharge condition. It must however be said, as visible in fig. 6, that the battery finds automatically the right state of charge not to overcome the maximum or minimum limit, because cuts in charge or discharge currents make the cycle unbalanced. When I/C_n was more than 9 A/Ah, the battery voltage stabilises at a level that makes the voltage cycle between minimum and maximum allowances, so this charge-discharge condition represents the maximum possible stress for the battery during tests of type 2.

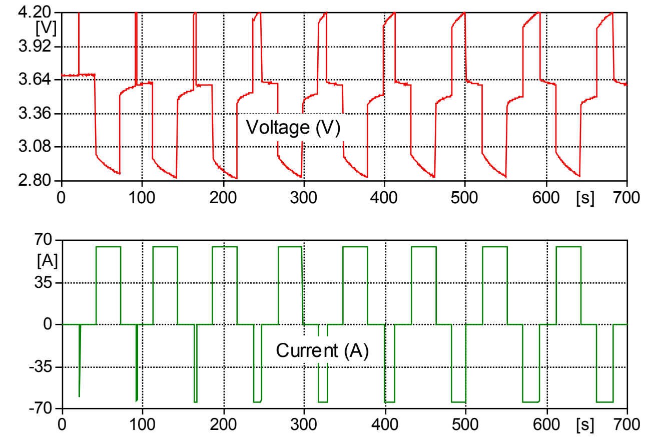

Fig. 6: Voltage and current during test of type 2 related to a current of 9 Cn. Cuts on current during first charge phases are clearly shown.

Finally tests of type 3 were performed.

The result obtained is shown in fig. 7, where measured battery current, battery and ambient temperatures are shown. The current was shaped in such a way that positive and negative peaks were equal, in A, to six times the nominal (one-hour) battery capacity.

It is clearly seen from these plots that this current stress does not cause important over-temperature in the battery, even though rare current peaks reach 6*Cn, not only during discharge (positive currents) but also in during charge (negative currents).

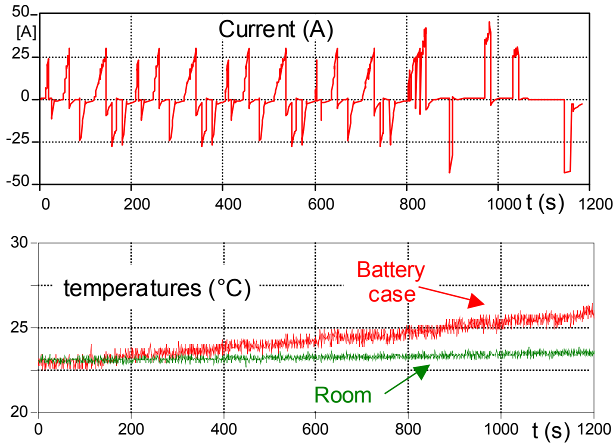

Fig. 7: Battery current and temperatures during a sample test of type 3.

It may be questioned that a current stress, reaching 6*Cn, much more than what considered acceptable by the manufacturer, is too stressful for the battery and could, therefore imply a short cycle life. Therefore, a cycle life test was carried out as discussed in the next section.

D. Experimental evaluation of cycle life

In the cycle life test the battery has been subjected to many (reduced-power) NEDC cycles, with periodic check of battery capacity, according to the pattern shown in fig 8, where several NEDC cycles are reported in the left part (roughly two per hour). The tests are arranged so that:

- After each NEDC cycle, a no-operation phase of 600 s is imposed, to verify the open circuit voltage and update to the previous state the quantity of charge inside the device. The charge current seen between, t=9,7 h and 9,78 h, and after 10,25 h have the purpose of slightly recharging the battery to compensate for the charge lost during discharge; the correspondence between open circuit voltage and state-of-charge is discussed in [8];
- after 136 NEDC cycles, corresponding to about 1400 km, a complete charge-discharge cycle is imposed, to verify the effective capacity of the device under stress.

After about 1000 cycles, equivalent to 10000 km, the reduction in terms of capacity is about 1,8% of the initial measured value, nearly of 10,8 Ah. It means, linearly extrapolating data, that the end of life for the device under stress could be estimated to be around 10000 NEDC cycles or 10^5 km. Obviously, since no guarantee exists of a linear behaviour of the battery, the test continue to get more accurate evaluation of batter life, under the considered stress.

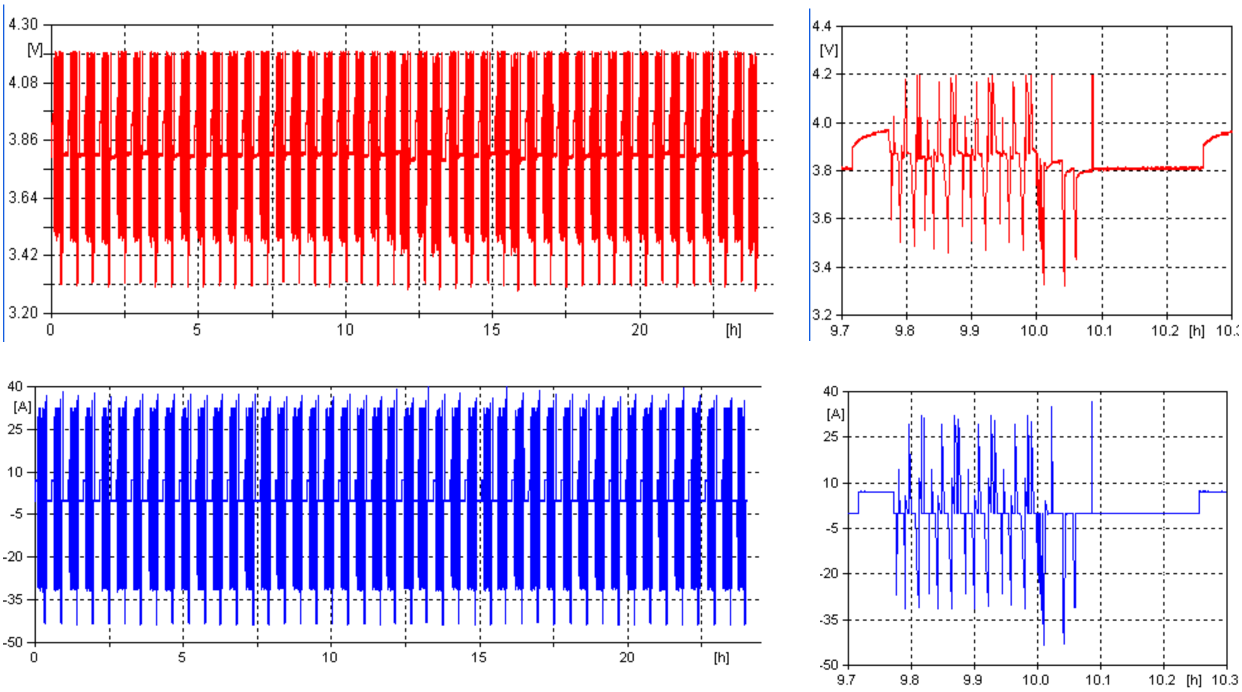

Fig. 8: Voltages (top) and currents (bottom) for the cycle-life test. The right plots are a zoom of zones from the left ones.

III. Conclusions

The paper has showed that commercially available ultra-high power lithium batteries are adequate for use as the sole energy storage onboard hybrid vehicles. The analysis involved a four step process:

1. the performance of the cell when subjected to deep high power discharges is in principle good, but shows poor charge performance; however this usage is far from the typical hybrid vehicle usage;
2. the performance under idealised shallow charge/discharge is much nearer to the actual vehicle usage, and shows better performance: shallow charge/discharge cycles should be possible at much higher currents than allows for full charge process;
3. the performance under a current cycle simulated the actual current profile onboard a vehicle covering a NEDC Cycle. This has indicated that peak currents to up to $6*C_n$ cause negligible cell temperature rise. These tests, however raise the question whether so high charge currents cause rapid battery ageing. Therefore the following point 4 was addressed;
4. cycle life of the cell under NEDC cycle was experimentally evaluated, giving very encouraging results: under a NEDC involving $6*C_n$ charge/discharge peak currents the battery should be able to cover at least 100000 km.

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