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Short communication

Lead–acid battery chemistry adapted for hybrid electric vehicle duty

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Abstract

Lead–acid batteries that are intended for traditional tasks such as SLI or deep cycle duty do not perform well in hybrid electric vehicles (HEVs). With the benefit of a few straightforward modifications in design, however, batteries deploying lead–acid chemistry can satisfy the performance requirements of power-assist HEVs in both bench- and in-vehicle tests.

Keywords: Hybrid electric vehicles; Power-assist; Lead–acid batteries; Design; Performance

1. Introduction

The lead–acid battery community anticipates a serious challenge during the next few years as its largest market, i.e. for SLI batteries, faces the prospect that conventional 12 V batteries will be substantially replaced by batteries designed for vehicles with a markedly higher electrical power requirement. The crux of the challenge is that neither conventional 12 V SLI batteries nor present generation deep-cycle batteries are able to perform the duty required by the new, high-power, automobile systems for an acceptable life. Batteries for these high-power systems will operate from a partial-state-of-charge baseline and will be discharged, and particularly re-charged, at extraordinarily high rates (albeit within a small range of state-of-charge). Within such duty, the life-limiting mechanism appears to involve the progressive accumulation of lead sulphate on the negative plate. This failure mode appears as a result of the very high rates of recharge and persists because the battery is not routinely returned to a full state-of-charge in the required duty. Partial-state-of-charge operation does bring one benefit, however, in that, at intermediate states-of-charge, charge-acceptance can be extremely high.

In order to offer an acceptable life in such applications, conventional designs of VRLA batteries must be revised. The battery must be able to sustain the negative plate charge reaction at very high rates, overcoming diffusion limitations (leading to reduced lead sulphate solubility etc.) which would otherwise lead to the onset of secondary reactions, such as hydrogen evolution, and charge inefficiency.

There are two straightforward design modifications that offer the potential to redeem this situation and to allow the lead–acid battery to perform successfully in the high-rate partial-state-of-charge (HRPSoC) routine demanded in hybrid electric vehicles [1]: The provision of an appropriate grid design allows the plates in the battery to accept the high charge rates required; and the incorporation of elevated concentrations of carbon (a few wt% instead of the traditional 0.2 wt%) alleviates the tendency for sulphate to accumulate, and appears to offer the route to a long operating life in the HRPSoC regime.

This paper provides an early indication of the successful operation of lead–acid batteries that incorporate these features, both in the laboratory and in hybrid electric vehicles on the road.

2. Grid design

The potential distribution (and hence the current density) across the plates of a battery of monopolar design is never uniform (Fig. 1). The current density gradients across the plate become steeper as the rates (of charge and discharge) at which the plate is being used increase. At the very high rates that are

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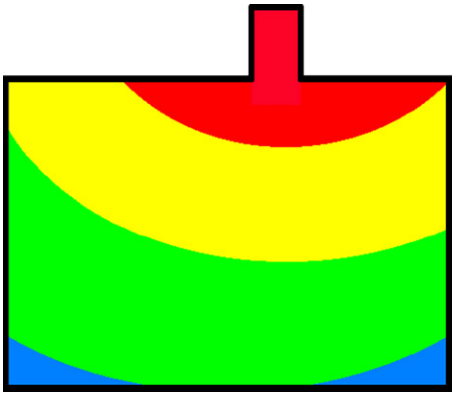

Fig. 1. Potential distribution of a conventional plate with a centre lug [2].

normal in hybrid electric vehicle duty, current can be so concentrated in the region adjacent to the current take-off lug that much of the plate (and much of the active material) is unable to contribute power. For conventional lead–acid batteries exposed to such treatment the consequence is an early failure due to heavy sulphation in those parts of the plate that are over-worked (the top) [3].

In order to operate under conditions of high-rate from the partial-state-of-charge condition that is necessary to enable the battery to accept charge from regenerative braking, conventional grid designs must be modified.

The simplest improvement change is to provide a second current take-off lug diametrically opposite the normal one. This allows a second region of the plate to operate at high current density, effectively doubling the capacity (and power) at high rates. An early test of this strategy demonstrated that a spiral wound cell with a second current take-off lug, when discharged at a rate of 31 C, could provide more than double the energy that could be obtained from a single lug version. Further, while a 36 V module of single lug cells exposed to a brutal HEV test regime failed after only 18 min, a 36 V module of the twin-lug equivalent cells, when exposed to the same test, was able to operate for 39 h continuously [4].

The development of grid designs has continued to make an outstanding contribution to the ability of lead–acid batteries to operate successfully in HEVs, as will be illustrated below.

3. Composition of the negative active mass

When conventional lead–acid batteries are exposed to HRPSoC duty they generally fail quickly as a result of the accumulation of lead sulphate on the negative plate. There is a concentration of the lead sulphate at the top of the plates, as described above. There is also a concentration of sulphate at the surface of the plates and this may have to do with diffusional limitations in the liquid phase. It has become clear that this second type of sulphate accumulation can be relieved to a considerable degree by adjusting the inventory of the minor components of the negative active mass. Specifically, the inclusion of 2 wt% of graphite (or 2 wt% graphite plus 2 wt% of carbon black) in place of the usual 0.2 wt% of carbon black improves the HRPSoC performance of the cells vastly. Valve-regulated lead–acid cells benefiting from such adjustments have demonstrated over 200,000 HEV duty cycles, equivalent to a cumulative energy throughput of about 5500 times the nominal capacity [5].

4. In-vehicle and ‘on the road’ tests in HEVs

4.1. *Micro–mild operation*

A 36 V pack consisting of six 6 V, 25 Ah spiral-wound cells containing elevated levels of carbon materials in their negative plates has been evaluated in a Ford Focus mild hybrid operated on a dynamometer [6]. The vehicle has been run repeatedly through a 1 min operating cycle that exposes the battery to a sequence with a maximum discharge of around 200 A and maximum charge of over 25 A, whilst maintaining the string in a ±1% SOC window, in this case around 40% SOC. At first, the voltage during charge events rises to 7.3 V per module but, after an hour of cycling, and for the remainder of the test, the voltage characteristic shows a significantly reduced charging voltage (Fig. 2), more closely mimicking the behaviour of nickel metal hydride cells in similar tests. This improvement may be due to internal changes in the module, but does not appear to be linked to a change in SOC (which is controlled) or ambient temperature (which was varied by −10 °C without significant effect). Further work is under way to investigate this. At the later point, the charge acceptance is strong and excursions to high voltage disappear.

4.2. *Medium-hybrid operation*

Energy storage system performance goals for power-assist hybrid electric vehicles have been proposed by the Freedom-

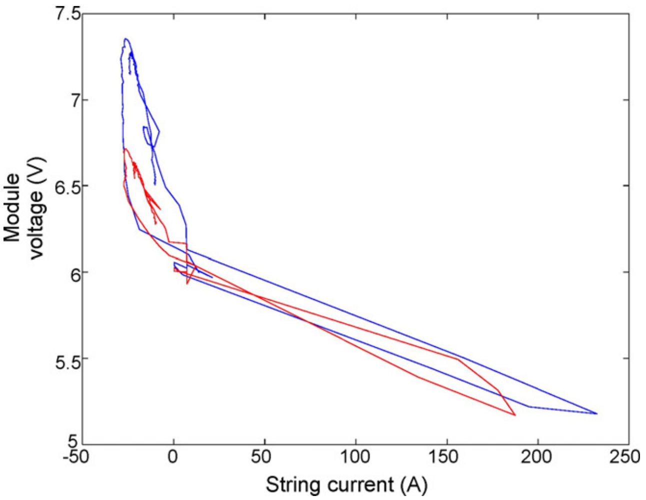

Fig. 2. Current–voltage plots for one module of a 36 V (6 × 6 V modules) 25 Ah, spiral-wound, battery pack in which the negative plates all contain elevated levels of carbon, operating in a Ford Focus mild hybrid on a dynamometer [6] on a cycle in which SOC is maintained to be 40 ± 1%. For the first few cycles, the module voltages climb to around 7.3 V during the charge part of the cycle as shown in the upper trajectory but, after about an hour, the voltage during charging reduces significantly as the lower trajectory shows, more closely mimicking the behaviour of nickel metal hydride batteries in a similar test. Note that current into the vehicle is shown as positive as is vehicle industry practice.

Table 1
Some key FreedomCAR energy storage system performance goals for power-assist HEVs [7]

Characteristic	Units	Minimum power-assist	Maximum power-assist
10 s Discharge power	kW	25	40
10 s Charge power	kW	20	35
Available energy	kWh	0.3	0.5
Weight	kg	40	60
Cycle life	Cycles	300,000	300,000
Derived parameters			
Specific discharge power	$W\,kg^{-1}$	625	667
Specific charge power	$W\,kg^{-1}$	500	583
Specific energy	$W\,h\,kg^{-1}$	7.5	8.3

Table 2
Batteries purpose-designed for high-rate partial-state-of-charge operation—as in power-assist hybrid electric vehicles, and their specific power performance

Battery type, manufacturer	Design elements	Specific power ($W\,kg^{-1}$)
'RHOLAB' (8 Ah), Enersys	Twin-tab to boost power, spiral wound	600
Bipolar (7 Ah), Effpower	Bipolar plate of porous ceramic impregnated with lead	1000
Ultra battery (8.5 Ah), Furukawa/CSIRO	Additional carbon capacitive element in common with negative plate	500–600

CAR team [7]. Some of the key parameters proposed are listed in Table 1. Combination of the power and energy targets with the proposed weight limitation allows the derivation of specific power and specific energy figures and these are also listed.

Batteries assembled with the relatively straight forward design elements outlined in Sections 2 and 3 exhibit maximum specific power values that are close to the derived targets for specific power (see Table 2), and the specific energy requirements are well within range. Such batteries have already been shown capable of performing 200–300,000 simulated HEV cycles without failing.

One hundred and forty four volt batteries of all three types shown in Table 2 have been running successfully in Honda Insight HEVs from which the original nickel metal hydride batteries have been removed.

The first vehicle mentioned in the Table has a battery of cells with twin tab grids as a first step towards an optimized HEV design. Further improvement can be expected in future stages of test when appropriate levels of carbon (graphite) will be included in the negative active material. The road test of this vehicle is the most advanced and, at the time of writing has completed over 30,000 miles of operation with the lead–acid battery and the test is continuing. An interesting feature of this battery's performance has been that, with the baseline pack SoC levels set at 60% the current voltage plots for the cells in the pack (Fig. 3) are again linear indicating an excellent charge acceptance during regenerative braking events.

The second vehicle benefits from a bipolar battery design and here of course the grid configuration is ideal for providing uniform active material. The battery occupies less volume in the vehicle than did the original nickel metal hydride (Fig. 4) and road tests with it, in Sweden, have been going well.

The Ultra battery is an interesting concept born of the observation that a super capacitor in parallel with a lead–acid battery copes extremely well with HRPSoC cycling [8]. In the Ultra battery, a carbon capacitor plate is attached to the negative plate

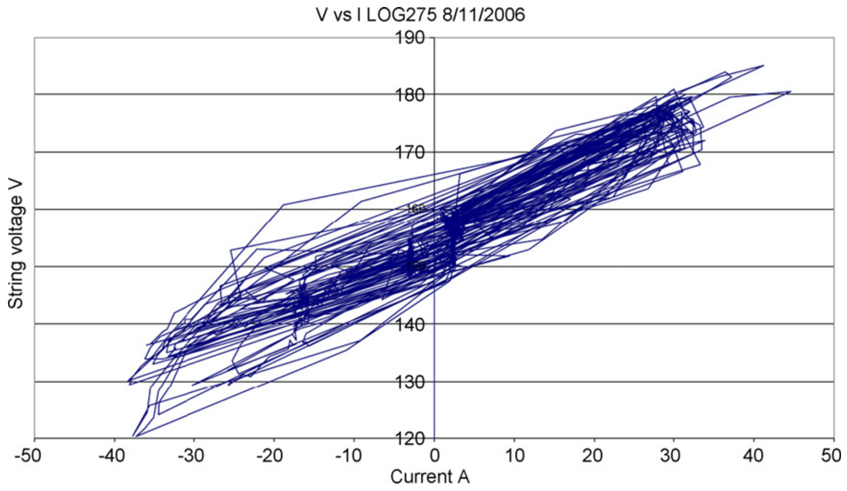

Fig. 3. Current–voltage plots from twin-tab spiral-wound cells comprising the 144 V battery operated around 60% state-of-charge in the first Honda 'Insight' listed in Table 2.

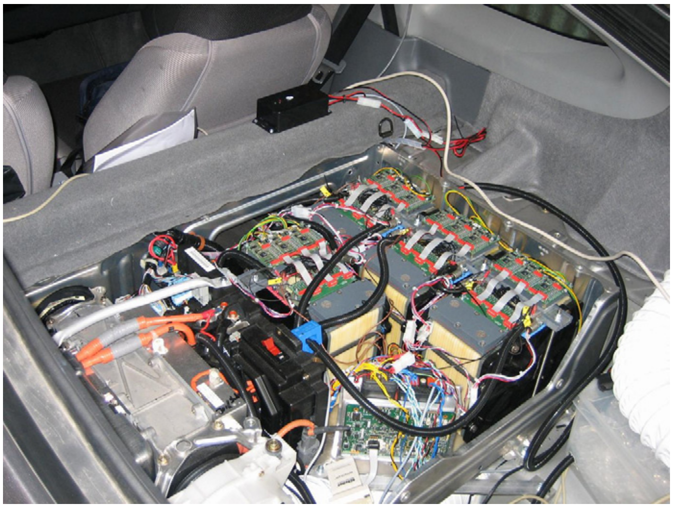

Fig. 4. Effpower bipolar lead–acid battery installed within the space vacated by the NiMH battery taken from Honda Insight No 2.

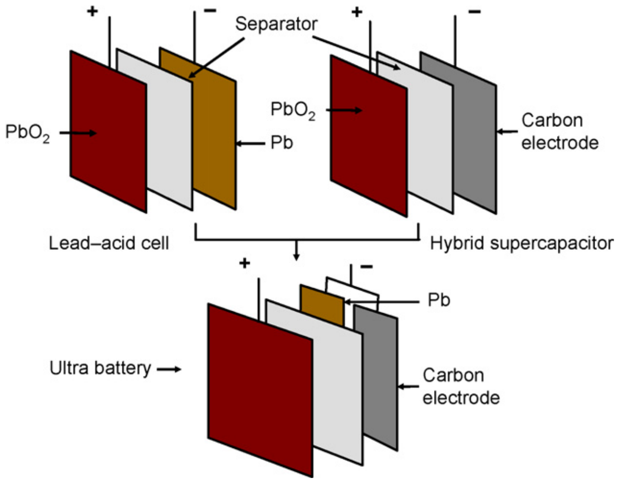

Fig. 5. Schematic diagram showing the configuration of Ultra battery.

Fig. 7. Vehicles 1 and 3 on road test at the Millbrook test track in the U.K.

and enclosed within a single battery casing (Fig. 5). Laboratory cycling of the Ultra has proved to be very successful [9], outperforming the battery in the first vehicle (above) in cycling tests, by a factor of 4. Prototype batteries of this design meet or exceed the FreedomCAR [10] targets for power, available energy (Fig. 6), cold cranking and self-discharge, for both minimum and maximum power-assist systems. This battery is now also on road test at the Millbrook test track (Fig. 7).

5. Conclusions

The behaviour of lead–acid batteries that have been designed for SLI or for deep cycle use is not a reliable indicator of how other forms of lead–acid-based batteries might function at high rates from a partial-state-of-charge. In fact, when designed specifically for purpose, batteries that make use of the lead–acid chemistry are quite capable of providing useful service in HRPSoC regimens. In the medium hybrid application (offering regenerative braking, and power-assist but little or no all-electric

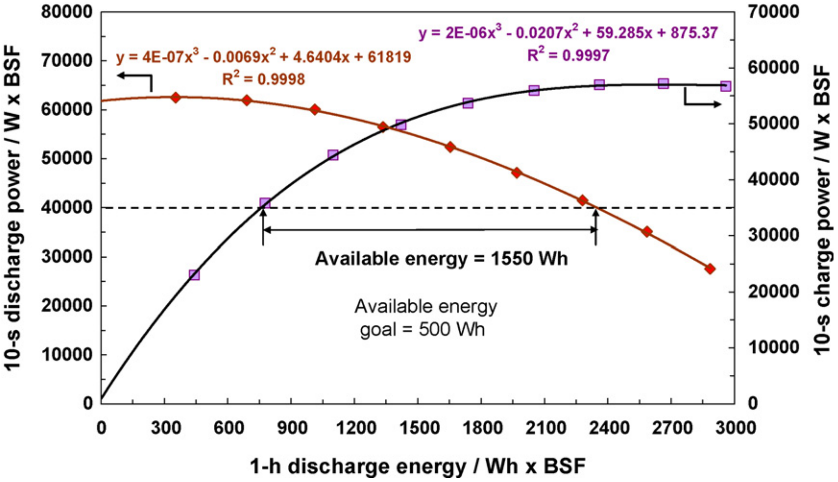

Fig. 6. Ultra battery hybrid pulse power characterization. Discharge power 25 kW, charge power 20 kW, battery size factor 35 [8].

range) the specific energy of the battery is less important than its ability to provide adequate power for an acceptable life. It appears that appropriate forms of lead–acid battery can cope with this task successfully.

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