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Short communication

The optimisation of grid designs for valve-regulated lead/acid batteries for hybrid electric vehicle applications

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ABSTRACT

The design, construction and testing of valve-regulated lead/acid cells with grid designs optimised for high-rate partial state-of-charge cycling for hybrid electric vehicles are described. Computer modelling was used to develop the grid designs. This showed that designs with opposed tabs and terminals on the top and bottom of the cell were likely to have the best performance not only in terms of grid conductivity but also for uniformity of active material utilisation. Prototype cells were built and tested. Low rate performance was in line with the designs and the high-rate performance was substantially enhanced compared with conventional constructions. The cells were then tested to a shallow cycling regime and to a simplified hybrid electric vehicle cycle. The results showed excellent life under these conditions without the benefit of carbon or graphite additives to the negative active material that have also been shown to improve cycle life under these conditions.

1. Introduction

The development of valve-regulated lead/acid (VRLA) batteries for application in hybrid electric vehicles (HEVs) has been directed towards the resolution of problems arising from the need to operate the battery in a partially discharged state in order to be able to accept charge from the vehicle for energy recovery. This high-rate partial state-of-charge (HRPSoC) operation leads to problems with the negative plate [1] which loses capacity because the lead sulphate discharge product tends to agglomerate or forms within the grid in locations where it cannot be readily recharged. Intermittent charging to a full state-of-charge may partially rectify the loss of capacity but in practice this is not a good solution and ways of improving the behaviour of the negative plate are being investigated. Two main approaches have been studied: first, to improve the conductivity of the negative active material by adding carbon or graphite in larger quantities and, second, to improve the grid design with the aim of decreasing the internal resistance of the cell. In the work described in this paper, the effects of changing the grid design not only to reduce internal resistance but also to ensure that the positive and negative electrodes are operating more uniformly have been studied. The effects of conductive carbon or graphite additives have not formed part of this study in order to identify the potential of improvements in grid design alone to enhance battery performance for HEV duty cycles.

The first part of the work was a finite element simulation of grid designs aimed at improving overall battery performance. This approach has been well developed [2,3] and in this case the model was validated experimentally with two iterations of simulation were carried out in order to arrive at a preferred design. A small cell suitable for HEV applications was then designed and built using grids laser cut from extruded sections. These were parameter tested at low and high rates prior to tests under shallow cycling and in a simplified HEV regime. The results of these tests are presented below.

2. Development and validation of a finite element cell model

A finite element model was established with lead grids with blocks of electrolyte between the grids. The grids used for this had a thicker side current collector and a central part with a reduced section containing the grid members. The electrolyte was only in contact with the area of the grids with grid members and active material and a block thickness of 20 mm was used to achieve perpendicular current flow through the block to emphasis the effectiveness of the grid design. The electrical constraints were a voltage of 1.0 V at both ends of the plate lugs and 0 V at the other side of the electrolyte block. The electrical conductivity of lead was taken as $2.06 \times 10^{-7}\,\Omega\,\text{m}$ and for the block $0.02\,\Omega\,\text{m}$. The model was of the grid in contact with electrolyte only and did not consider the

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effect of the active materials as the purpose was to optimise the grid design. ANSYS 10 software was used with free-meshed quadratic tetrahedral elements having a maximum side length in the grid of 2 mm and 5 mm in the block. In the first instance, an existing grid design was used for the simulation and the results were compared with the measurements made on an actual grid. The voltage and current distributions were calculated. For the experimental set-up a grid was immersed in 5 M sulphuric acid and measurement was made at 2 kHz so that calculated and actual values could be compared. The measured values differed from the calculated values by ~5% and the sum of the deviations (positive and negative) was close to zero. Furthermore, the deviations were random rather than systematic and as a result the simulation was judged to be capable of providing a reasonable basis for comparison between grid designs.

3. Computer simulation of grid designs

The first sequence of simulations was carried out to determine which combination of grid design and cell layout relative to lug position provided the best starting point for subsequent optimisations. For each arrangement, a map of current density per unit area and voltage distribution was generated but the assessment of these becomes subjective and three parameters were measured to quantify the evaluation. These were:

(i) j_{mean}, the mean current density between the grids.
(ii) σ_j, the standard deviation of the current in the electrolyte.
(iii) ΔU_{max}, the maximum voltage drop in a grid.

Different arrangements of the side current collector were simulated: (i) with single tabs on the same side at the top, (ii) with single tabs on opposite sides at the top, (iii) with single tabs on the same side at top and bottom, (iv) with single tabs on opposite sides at top and bottom, (v) with double tabs on the same side and (vi) with double tabs on opposite sides. For these types radial and rectangular grid designs were compared. Central current collectors were simulated with single tabs at the same and opposite sides and also double tabs. The thickness of the side current collector was also varied.

Sorting the results by j_{mean} provides a measure of total cell efficiency and the double lug designs were ranked highest, followed by the double tab designs with a central current collector. The radial designs did not provide significant improvements but the designs were not optimised. Sorting the results by σ_j shows the best performance with tabs on opposite sides. In this case the cells are optimised for uniform current distribution which in turn provides optimum mass utilisation but the ranking number has two factors which need to be considered in interpreting the results. First, the standard deviation measures the absolute width of the distribution and designs with a higher current density are treated less favourably and, second, with central current collectors, there are two additional edges and, in turn, double the number of outlying values. Finally, sorting the results by ΔU_{max} shows that designs with double tabs are superior and, as above, radial designs were not especially beneficial. Overall, these data showed that designs with opposed tabs had the best performance.

Following this iteration a further simulation was carried out in each case (unless prevented by the nature of the cell design) with tabs in line, tabs vertically opposed, tabs diagonal and tabs opposite to each other as in a conventional design. The variations considered were (i) two side tabs of 15 mm width or one side tab of 25 mm width with the top section tapered away from the tabs and tapered wires, (ii) conventional tabs, (iii) varying the width of the current collector from 8 to 12 mm, (iv) adding tapered wires in 0.5 mm steps from 1.0 mm (no taper) to 2.5 mm, (v) adding more horizontal wires, (vi) radial designs with dual and single side tabs and (vii) using hexagonal pellets across the whole grid with a 1.0 mm wire and an area of 72 mm^2. These were analysed as before and the selected design had opposed single tabs and tapered wires. Similar conclusions have been reached by earlier studies [4] but have not been evaluated under an HRPSoC duty cycle. The basis of selection was both for performance and ease of manufacture.

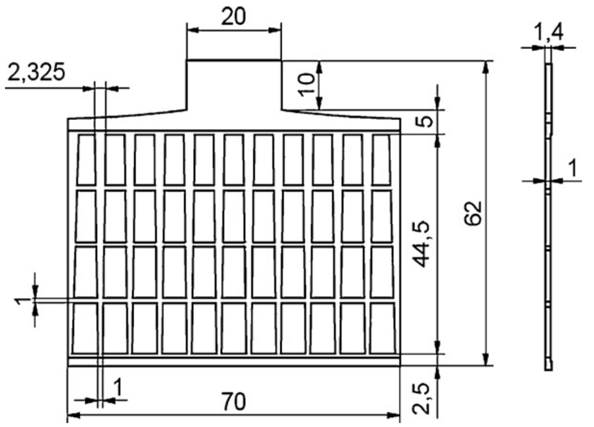

Fig. 1. Preferred positive grid design. The negative used the same design except that the overall thickness was 1.2 mm in the wider section and 0.8 mm in the centre. The grid section was extruded with a thinner section in the centre and the active material pasted flush to the thicker section. The vertical wires were tapered towards the lug and top bar increased in depth towards the lug. The plates were arranged with the negative plates opposed to the positive plates with the lugs opposite.

Fig. 2. Prototype cell. The terminals are on the top and bottom of the cell which has a closure on both sides of the cell and a Bunsen valve vent on one side only.

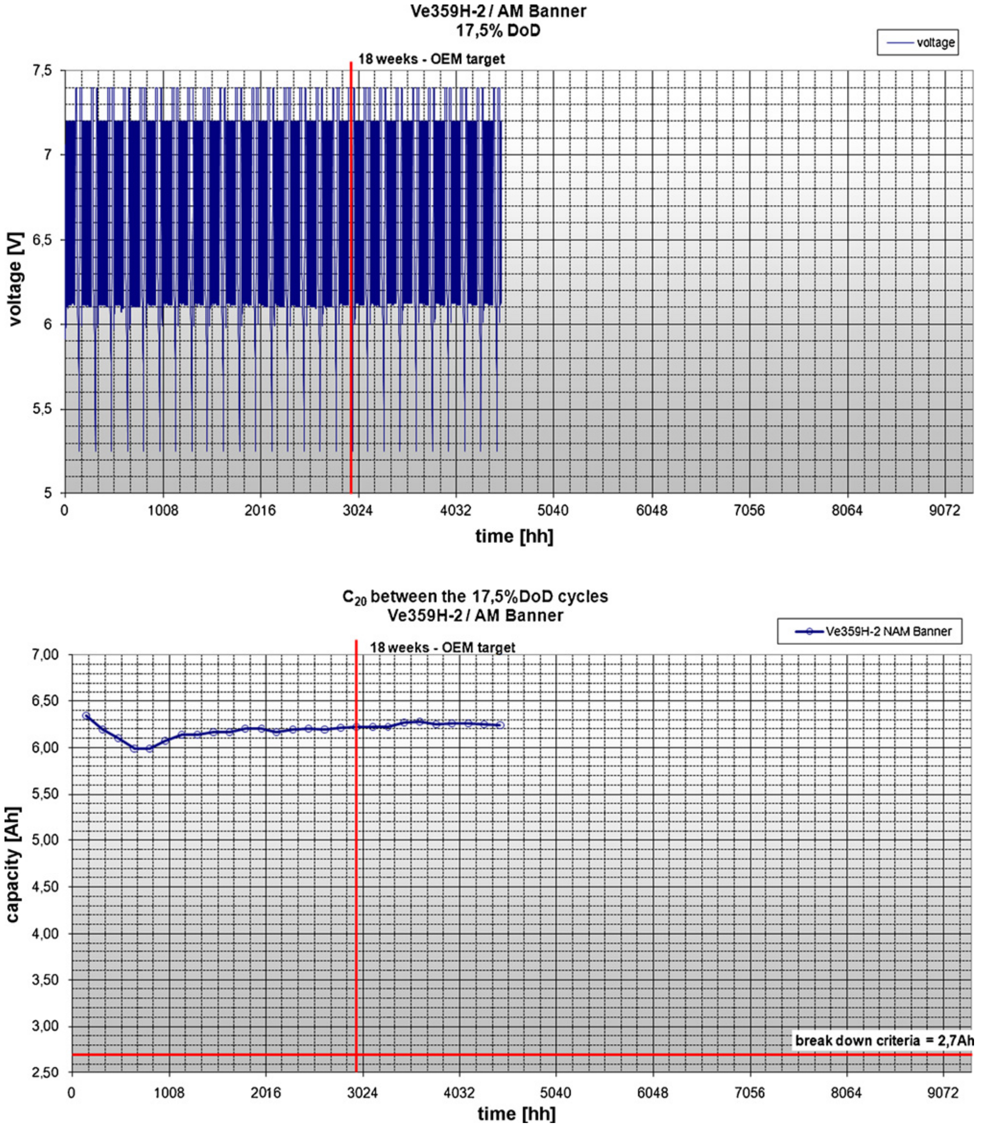

Fig. 3. Shallow cycling (17.5% depth-of-discharge) test data. Voltage profile (above) and 20 h capacity (below) against time.

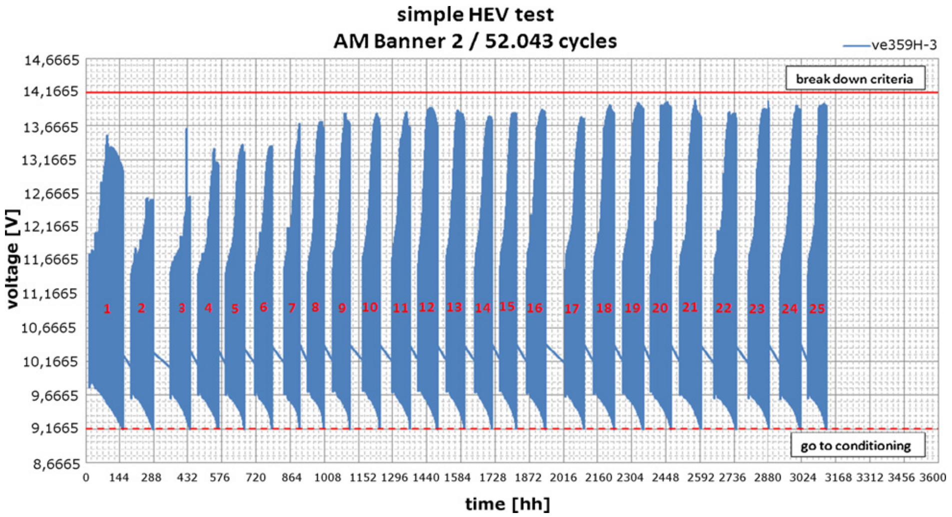

Fig. 4. Simplified hybrid electric vehicle test results. The cells were cycled until they reached 1.83 V per cell and then subjected to a conditioning cycle in which the capacity was measured. Over 52,000 cycles have been completed and the cells are continuing to cycle.

4. Cell design

The cell was designed to have a nominal capacity of 5.4 Ah and was sized to fit in battery box with thermal control for a commercially available HEV. The design used four positive plates and five negative plates, horizontally opposed with terminals at the top and bottom of the cells. The selected grid design had a 20 mm tab and the vertical wires were tapered from 2.3 to 1.0 mm. The grid material was extruded so that the top and bottom sections were 0.4 mm thicker than the centre and the central section was flush pasted (Fig. 1). The grid alloy was Pb–0.04% Ca–1.2% Sn and the active materials were standard. An absorptive glass mat separator with a high fine fibre content was selected. The cells were built manually and had pillars with brass female inserts. The containers and lids were moulded in acrylonitrile butadiene styrene copolymer and the lids secured with epoxy resin. A Bunsen valve was used incorporating a sintered polyethylene flame retardant disc (Fig. 2). The cells were processed under standard conditions.

5. Electrical performance

5.1. Initial performance

The 20 h capacity of the cells at 25 °C was 5.7 Ah on a first test and 6.1 Ah on a second test. The high-rate performance at −18 °C to EN 50342-1: 2006 was between 100 and 125 A. This is substantially more pro-rata to low rate capacity than a conventional VRLA automotive battery because of the improved grid designs. The 2 h capacity of the cells was 4.9 Ah.

5.2. Cyclic performance

Groups of cells were tested at room temperature under shallow cycling conditions to a depth-of-discharge of 17.5% with a capacity check at the 20 h rate after each 85 cycles. The test sequence was as follows:

(i) Discharge at 0.2 C for 2.5 h with an end voltage limit of 1.67 V per cell.
(ii) Recharge at 0.35 C for 40 min with a top-of-charge voltage limit of 2.40 V per cell.
(iii) Discharge at 0.35 C for 30 min with an end voltage limit of 1.67 V per cell.
(iv) Repeat steps (ii) and (iii) 85 times.
(v) Charge at 0.1 C for 18 h with a top-of-charge limit of 2.47 V per cell.
(vi) Discharge at 0.05 C to 1.75 per cell.
(vii) Charge at 0.1 C for 23 h with a top-of-charge voltage limit of 2.47 V per cell.
(viii) Repeat steps (i)–(vi) until the battery reaches 50% of the nominal 20 h capacity.

This test is used as a qualification test for batteries for stop&start duty cycles for automotive applications with an acceptance level of 18 units. The results are shown in Fig. 3 where the capacity was very stable up to 27 units (430 capacity turnovers) and the cycling was being continued and in testing with an earlier group of cells where the plate processing had not been fully optimised, the capacity after 57 units (905 capacity turnovers) remained at 56% of nominal. These data show that the performance of these cells is substantially better than standard VRLA batteries with the same active materials which achieve the 18 unit specification but without significant margin unless modified by the addition of carbon or graphite to the negative active material.

A number of cells were subjected to a simplified HEV cycle test to assess the degree to which the negative plates polarize on shallow cycling. This test cycled the cells between 50 and 53% state-of-charge with 10 s rests between 1 min charge and 1 min discharge cycles. When the voltage at the end of the discharge pulse reached 1.83 V per cell, the cells were recharged and allowed to restart the test after a capacity measurement and cell conditioning cycle. The capacity was measured at the 1 h rate. This test is normally carried out in a water bath at 25 °C but because the cells had terminals at both ends, the test was carried out at ambient temperature. The test sequence was as follows:

(i) Discharge at 1 C at 25 °C to 1.75 V per cell.
(ii) Recharge at 0.2 C for 16 h with a top-of-charge voltage of 2.47 V per cell.
(iii) Discharge at 1 C to 50% of nominal capacity.
(iv) Rest for 10 s.
(v) Charge at 2 C for 60 s; terminate the test if the voltage exceeds 2.83 V.
(vi) Rest for 10 s.
(vii) Discharge at 2 C for 60 s.
(viii) Repeat (iv)–(vii) until the voltage reaches 1.83 V per cell and then go to (ix).
(ix) Discharge at 1 C to 1.75 V per cell to determine the residual capacity.
(x) Recharge as (ii).
(xi) Discharge as (i) to determine actual capacity.
(xii) Recharge as (ii).
(xiii) Discharge as (iii).
(xiv) Recommence cycling from step (iv).

The results are shown in Fig. 4. The cells had completed 52,043 cycles in 25 units and retained a capacity of 76% of the nominal 1 h rate. Data for a standard VRLA automotive battery using the same active materials showed that only 3815 cycles or 2 units were completed with a retained capacity of 12% of the nominal 1 h rate. The battery failed immediately in the third cycle.

6. Conclusions

The conclusions from this study are remarkably clear and simple. If the cell design for a VRLA battery is modified to have a much lower internal resistance by the use of a higher ratio of grid metal to active material than in a conventional construction with an optimised grid design and the cell is designed, in this case by the use of opposed tabs for current take-off, to ensure that the active material is utilised uniformly, then the life under HRPSoC cycling can be substantially improved. This can be achieved without modification of the negative active material by the addition of higher levels of carbon or graphite. Tests carried out by NorthStarBattery [5] with VRLA batteries with improved current collectors (but not to the same degree as used in this work) and carbon additives to the negative plates, gave endurance levels on the same simplified HEV cycling test used in this study of ~14,000 cycles compared with 1000–3000 cycles with unmodified batteries. Tests reported with a hybrid VRLA battery/supercapacitor energy storage device [6] gave 4300 cycles for a control VRLA battery with 2% carbon added to the negative plate and 18,000 cycles for the hybrid device, again to a similar test regime. For the future, the cell design may be further optimised and the effects of adding carbon or graphite to the negative plate investigated to determine if the benefits of this approach can be combined with improved grid and cell design to further improve battery performance for HEV applications.

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