ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Journal of Power Sources 144 (2005) 552–559

JOURNAL OF POWER SOURCES

www.elsevier.com/locate/jpowsour

Novel technique to ensure battery reliability in 42-V PowerNets for new-generation automobiles

L.T. Lam*, N.P. Haigh, C.G. Phyland, T.D. Huynh

CSIRO Energy Technology, Box 312, Clayton South, Vic. 3169, Australia

Abstract

The proposed 42-V PowerNet in automobiles requires the battery to provide a large number of shallow discharge–charge cycles at a high rate. High-rate discharge is necessary for engine cranking, while high-rate charge is associated with regenerative braking. The battery will therefore operate at these high rates in a partial-state-of-charge condition — ‘HRPSoC duty’.

Under simulated HRPSoC duty, it is found that the valve-regulated lead–acid (VRLA) battery fails prematurely due to the progressive accumulation of lead sulfate mainly on the surfaces of the negative plates. This is because the lead sulfate layer cannot be converted efficiently back to sponge lead during charging either from the engine or from the regenerative braking. Eventually, this layer of lead sulfate develops to such extent that the effective surface area of the plate is reduced markedly and the plate can no longer deliver the high-cranking current demanded by the automobile.

The objective of this study is to develop and optimize a pulse-generation technique to minimize the development of lead sulfate layers on negative plates of VRLA batteries subjected to HRPSoC duty. The technique involves the application of sets of charging pulses of different frequency. It is found that the cycle-life performance of VRLA batteries is enhanced markedly when d.c. pulses of high frequency are used. For example, battery durability is raised from ∼10 600 cycles (no pulses) to 32 000 cycles with pulses of high frequency. Two key factors contribute to this improvement. The first factor is localization of the charging current on the surfaces of the plates — the higher the frequency, the greater is the amount of current concentrated on the plate surface. This phenomenon is known as the ‘skin effect’ as only the outer ‘skin’ of the plate is effectively carrying the current. The second factor is delivery of sufficient charge to the Faradaic resistance of the plate to compensate for the energy loss to inductance and double-layer capacitance effects. The Faradaic resistance represents the electrochemical reaction, i.e., conversion of lead sulfate to lead. The inductance simply results from the connection either between the cables and the terminals of the battery or between the terminals, bus-bars, and the lugs of the plates. The capacitance arises from the double layer which exists at the interface between the plate and the electrolyte solution. These findings have provided a demonstration and a scientific explanation of the benefit of superimposed pulsed current charging in suppressing the sulfation of negative plates in VRLA batteries operated under 42-V PowerNet and hybrid electric vehicle duties.

A Novel Pulse™ device has been developed by the CSIRO. This device has the capability to be programmable to suite various applications and can be miniaturized to be encapsulated in the battery cover.

Keywords: 42-V PowerNet; Failure mode; High-rate partial-state-of-charge duty; Pulse-generation device; Hydrogen evolution; Lead–acid battery; Sulfation; Skin effect

1. Background

Within the next decade, there will be major changes in automotive technology with the introduction of several new features which will increase significantly the on-board power requirements [1]. This high power demand is beyond the capability of present 14-V alternators and thus a 42-V power network is to be adopted. In the new ‘PowerNet’, the battery must provide a large number of shallow discharge–charge cycles at a high rate. High-rate discharge is necessary for engine cranking, while high-rate charge is associated with

---

* Corresponding author.
E-mail address: lan.lam@csiro.au (L.T. Lam).

0378-7753/$ – see front matter © 2004 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2004.11.028

Fig. 1. The Novel Pulse^{TM} device developed in the CSIRO.

regenerative braking. The battery will therefore operate at these high rates in a partial-state-of-charge condition, so called 'HRPSoC duty'. Under such duty, there is a tendency for the plates — particularly the negative plates — of valve-regulated lead–acid (VRLA) batteries to suffer from a build-up of 'hard' lead sulfate, i.e., lead sulfate which is difficult to recharge. This effect can impair battery performance and life, and can reduce charge-acceptance during regenerative braking. Moreover, the problem of over-sulfation is exacerbated during prolonged parking of the vehicle.

A pulse-generation technique has been devised in an attempt to minimize the development of hard sulfate during both HRPSoC duty and stand conditions (Fig. 1). The technique involves the application of sets of charging pulses of different frequency to the battery. The device could be powered by an integrated starter and generator (ISG), a small solar panel, or a small of supercapacitor. In the last-mentioned option, the supercapacitor is kept predominantly at a full SoC, either by the ISG or by regenerative braking during vehicle running, and is sized to provide continuous power for operation of the pulse-generation device even when the vehicle is parked for periods of several days.

2. Experimental

2.1. 42-V profile (HRPSoC Cycling)

Studies were conducted on 12-V, commercial VRLA batteries ($C_{20} = 33$ Ah). One cell of each battery was fitted with a Ag | Ag_2SO_4 reference electrode [2]. The batteries were then subjected to the 42-V profile shown in Fig. 2 [3–6]. The duration of the profile is short, namely, 2.35 min. The profile is composed of several current steps that simulate the power required from the battery during vehicle operation, i.e., idle–stop, cranking, power assist, engine charging, and regenerative charging. The critical steps are the cranking and regenerative charging periods. During cranking, the battery must deliver a current of 300 A for 0.5 s, i.e., a current equal to $\sim 18C_1$.

The batteries were placed in a water bath which was maintained at 40 °C. Prior to the test, the batteries were brought to a fully charged state by applying a maximum current of 2.5 A and a constant voltage of 14.7 V for a total of 24 h. The batteries were then subjected to repetitive applications of the 42-V profile. Each application was considered to be 'one cycle' and a maximum of 1200 cycles was applied. The test was terminated when the batteries could not sustain at least 960 cycles (i.e., 80% of 1200 cycles) due to decrease in the end-of-discharge voltage to the cut-off value of 9.6 V during cycling. Otherwise, the batteries were charged fully and then subjected to a further set of 1200 cycles.

2.2. Teardown analysis

After battery failure under the 42-V profile, a detailed examination was conducted to determine the distribution of lead sulfate across cross-sections of negative and positive plates in both discharged and charged states. The samples, which were taken from plates in the outermost cell below the negative terminal, were mounted in epoxy resin to allow preparation of polished cross-sections for electron probe micro-analysis (EPMA). The five remaining cells in the battery were then subjected to a full charge. After charging, samples were taken from the cell adjacent to the outermost cell and then prepared for EPMA by means of the same procedure as that used for discharged samples. Thus, obviously, samples in discharged and charged states were obtained from different plates in different cells. Data on elemental abundance were acquired with a Joel Model JXA-8900R Superprobe which was operated at an accelerating voltage of 15 kV and a nominal beam current of 50 nA. Analyses were conducted for lead, sulfur, and oxygen.

3. Results and discussion

3.1. Performance of VRLA batteries without/with pulses of low frequency

Batteries without (VR1, VR2) or with (VR3 to VR5) low-frequency pulses (0.01–0.90 kHz) during discharge and charge of the 42-V profile failed prematurely at between 10 000 and 10 650 cycles (Fig. 3). Examples of performance of VRLA batteries VR2 and VR3 under repetitive 42-V duty are given in Figs. 4 and 5. Within each set, the charge-to-discharge ratio (c:d ratio) of the battery is always low initially, but increases rapidly to a value of ∼1.03. For a given set, the internal resistance of the battery increases with cycling. Furthermore, this change in internal resistance increases with the application of successive sets. For example, the internal resistance reaches ∼9 mΩ in the ninth set as opposed to ∼7 mΩ in the first set. The increase in internal resistance with cycling suggests a build-up of lead sulfate in the negative/positive plates which cannot be reduced/oxidized completely even during full charging.