J Appl Electrochem (2008) 38:77–82
DOI 10.1007/s10800-007-9403-4

ORIGINAL PAPER

# Comparative study of lead-acid batteries for photovoltaic stand-alone lighting systems

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Received: 18 April 2007 / Revised: 13 August 2007 / Accepted: 22 August 2007 / Published online: 14 September 2007


**Abstract** The lead-acid battery is often the weakest link in photovoltaic (PV) installations. Accordingly, various versions of lead-acid batteries, namely flooded, gelled, absorbent glass-mat and hybrid, have been assembled and performance tested for a PV stand-alone lighting system. The study suggests the hybrid VRLA batteries, which exhibit both the high power density of absorbent glass-mat design and the improved thermal properties of the gel design, to be appropriate for such an application. Among the VRLA-type batteries studied here water loss for the hybrid VRLA batteries is minimal and charge-acceptance during the service at high temperatures is better in relation to their AGM counterparts.

**Keywords** AGM-VRLA battery · Flooded-electrolyte lead-acid battery · Gelled-electrolyte VRLA battery · Hybrid VRLA battery · Photovoltaic lighting

## 1 Introduction

It is estimated that earth constantly receives 96 billion kW of power [1]. If this colossal and unlimited energy could be more fully utilized, our dependence on the fast dwindling fossil fuel cache will be drastically reduced. Solar energy is available in various forms such as direct solar radiation, wind, wave, rain (in the form of hydropower), photosynthesis and ocean thermal gradients [2]. Among these, the direct generation of electricity from solar radiation through solar cells is clean and attractive [3]. However, due to the intermittent nature of solar radiation, efficient and economic management of electrical energy requires its storage.

The storage and retrieval of electrical energy is most conveniently accomplished at present with storage batteries. There are several types of storage batteries, but it is the lead-acid battery, which predominates when the requirement is for stored energy of more than a few 100 W-h because no other battery is yet able to compete on cost grounds [4, 5]. However, in photovoltaic (PV) installations, the lead-acid battery is often the weakest link owing to its limited cycle-life and hence its premature replacement [6–17].

This communication describes a study conducted on the performance of hybrid VRLA, absorbent-glass-mat (AGM) VRLA, gelled-electrolyte VRLA, and flooded-electrolyte versions of lead-acid batteries for a PV application, namely stand-alone solar-lighting during February 2005 and June 2006. The study suggests the hybrid VRLA batteries to be most appropriate among all the aforesaid battery types.

## 2 Experimental details

### 2.1 Preparation of plates

Both positive and negative plates for the batteries were prepared using Pb–Ca–Sn–Al alloy (0.1% of Ca, 1.2% of Sn and 0.03% of Al) grids. The batteries were assembled in ABS containers using 1.25 specific gravity aq. $H_2SO_4$ as

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electrolyte. In brief, the positive plate paste was prepared by mixing leady oxide (85 wt.%), sodium carboxy methyl cellulose (0.15 wt.%), Dynel fibers (0.05 wt.%), and aq. $H_2SO_4$ of 1.4 specific gravity (7 wt.%) with de-ionized water (7.8 wt.%). The negative plate paste was prepared by mixing leady oxide (83 wt.%), lignin (0.2 wt.%), barium sulfate (0.15 wt.%), Dynel fibers (0.05 wt.%), graphite powder having average particle size of 40 μm (2 wt.%) and aq. $H_2SO_4$ of 1.4 specific gravity (7 wt.%) with de-ionized water (7.5 wt.%). The paste densities for positive and negative plates were 4 and 4.4 g $cm^{-3}$, respectively. After pasting the active materials onto the grids, the plates were subjected to hydrothermal curing at ~95% humidity at 65 °C for about 24 h. Subsequently, the plates were dried in the curing chamber at 65 °C for about 12 h. The lugs of the plates were cleaned with a buffing machine prior to their group burning.

### 2.2 Battery assembly and formation

Cell configurations for AGM VRLA, gelled-electrolyte VRLA, hybrid VRLA and flooded lead-acid batteries are presented in Table 1. Inter-electrode distances in AGM VRLA, gelled-electrolyte VRLA, hybrid VRLA and flooded lead-acid types were 1.85, 3.4, 3.4 and 3.4 mm, respectively. AGM and polyethylene (PE) separators were obtained from Nippon Sheet Glass Co., Japan and Super-Tech Battery Components Pvt. Ltd., India, respectively. 12 V-monobloc batteries were assembled by connecting six cells in series by group burning and housing them in commercial grade polypropylene containers. The batteries were made positive limited to facilitate oxygen recombination at the negative plates. The dimensions for batteries were: 350 mm length × 167 mm width × 174 mm height.

Sulfuric acid used for formation of AGM-type batteries was 1.23 sp. gr. while it was 1.21 sp. gr. for gelled-, hybrid- and flooded-type batteries. Prior to their formation, cells were filled with the required amount of sulfuric acid and kept for 2 h for electrolyte soaking. The batteries were formed by charging them galvanostatically at C/10 rate for 48 h followed by their discharge at C/5 rate using an automated Bitrode voltage/current source interfaced to a data-acquisition system. Subsequent to their formation, excess electrolyte was removed from AGM- and hybrid-type batteries; electrolyte was replaced with 1.25 sp. gr. in flooded-type batteries. Electrolyte was replaced by filling about 600 mL of gel obtained by mixing 1.25 sp. gr. sulfuric acid and M-5 CAB-O-SIL® fumed silica in gelled-type batteries. About 150 mL of gel was added in hybrid-type batteries. Gelled- and hybrid-type batteries were kept for about 24 h for the gel to form and settle. As the gel stiffens, it shrinks and leads to the formation of numerous micro-fine cracks, which facilitate the oxygen generated at the positive plates in the cell to diffuse to the negative plates. The batteries in their respective configuration were then charged galvanostatically at C/10 rate (charge input = 110%) and then discharged at C/5 using the voltage/current source. The charge/discharge cycles were continued until the batteries attained a stable capacity.

### 2.3 Battery monitoring and data collection

All the hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries were fitted separately to street-lighting solar photovoltaic (SPV) panels having two sub-panels each of which comprised 36 silicon cells as shown in Fig. 1. The impedance of each sub-panel was 2.35 Ω with $V_{mp}$ (voltage at maximum

**Table 1** Design characteristics of hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries employed for the solar-lighting service study

| S. No | Component | Battery-type | | | |
|---|---|---|---|---|---|
| | | AGM | Gel | Hybrid | Flooded |
| 1 | No. of positive plates | 5 | 4 | 4 | 4 |
| 2 | No. of negative plates | 6 | 5 | 5 | 5 |
| 3 | Pitch length (inter-electrode distance) (mm) | 1.85 | 3.4 | 3.4 | 3.4 |
| 4 | Separator | AGM separator of 2.2 mm thickness compressed up to 1.85 mm | Polyethylene separator of 3.4 mm thickness | AGM separator of 2.2 mm thickness wrapped on negative-plate; AGM separator of 1 mm thickness wrapped on positive-plate | Polyethylene separator of 1.3 mm thickness; negative plates wrapped with AGM separator of 1 mm thickness |

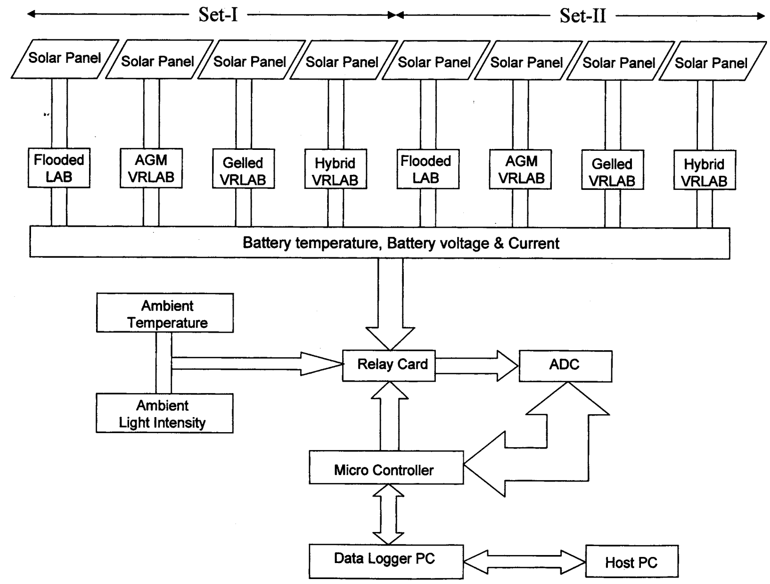


**Fig. 1** Schematic for data logging system employed to monitor battery performance for solar-lighting application

power) = 17 V, $I_{sc}$ (short-circuit current) = 2.5 A, and $P_{max}$ (maximum power) = 40 W ± 10%. The energy in each of the batteries was used separately to light an 11 W CF lamp during night (18:00–6:00 h). The batteries were charged during the daytime with the depth-of-discharge (DoD) varying between 25% and 30%. The batteries studied here were designed in such a way that they performed for minimum three nights continuously without any charging. Provision was also made to collect battery temperature (both ambient and cabinet), current, voltage, energy input and intensity of solar radiation. Provision was made to reduce the charging current when the batteries attained the maximum voltage of 14.1 V (2.35 V/cell) during charging. All the experiments were conducted on two sets of batteries. Both the sets (Set I and Set II) comprised a hybrid VRLA battery, an AGM VRLA battery, a gelled-electrolyte VRLA battery and a flooded-electrolyte lead-acid battery as shown in Fig. 1.

### 2.4 Battery weight-loss and state-of-health measurements

To determine the weight loss during the service life of hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries during their application in the solar-lighting system, the initial and final battery weights were obtained on an electronic balance having an accuracy of ±10 g.

To estimate the state-of-health (SoH) of the hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries during the service, the initial and final capacities of the batteries were obtained by using a Bitrode Model LCN cycle-life tester. For this purpose the batteries charged through the respective SPV panel were discharged at C/5 rate up to 10.5 V (DoD = 100%) at 30 °C.

## 3 Results and discussion

During the stand-alone solar lighting study, the charging profile of the batteries varies depending on the climatic conditions. Typical charging data for hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries on a clear day and a cloudy day during the study are shown in Fig. 2a and b, respectively. The respective solar-lux data are shown in Fig. 3a and b. Typical battery discharge profiles on a clear and a cloudy day are also shown in Fig. 4a and b, respectively.

On an average, the charge input to a battery on a clear day and cloudy day is found to be ∼ 22 and ∼12 Ah, respectively. The percentage overcharge is found to be about 10% more than the previous discharge during a clear day. This observation is in accordance with the lux data presented in Fig. 3a and b. During the test period, the lux value is found to vary between $1 \times 10^3$ and $1.2 \times 10^5$ lm $m^{-2}$ while the temperature varies between 25 and 45 °C. Unlike battery charge profiles, the battery discharge profiles are characteristically similar for all the battery types but for their initial and final output voltages. It is noteworthy that solar radiation consists of direct beam and indirect beam radiations. The direct beam radiation comes from the direction of the sun and is prominent on a clear day. The indirect beam solar radiation is broken up by clouds and dust, and comes from all directions, and is prominent on cloudy days [18]. Accordingly, any study on batteries for SPV application could be site centric.

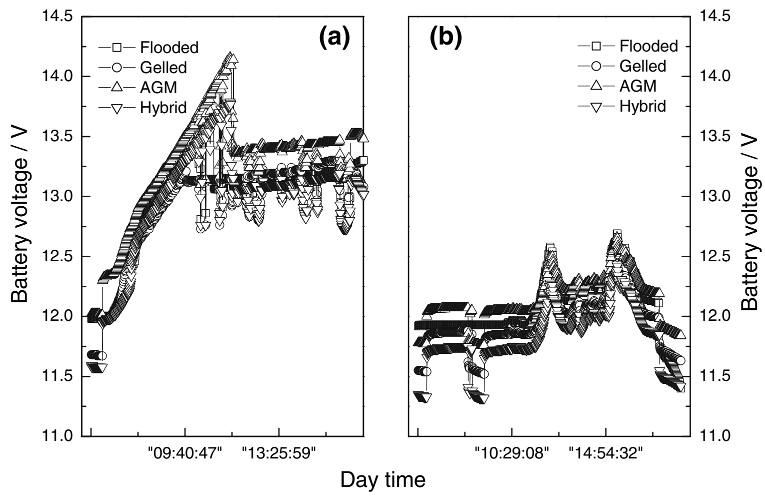


**Fig. 2** Typical charge data on (**a**) a clear day and (**b**) a cloudy day for various type of lead-acid batteries employed during the present solar-lighting application study

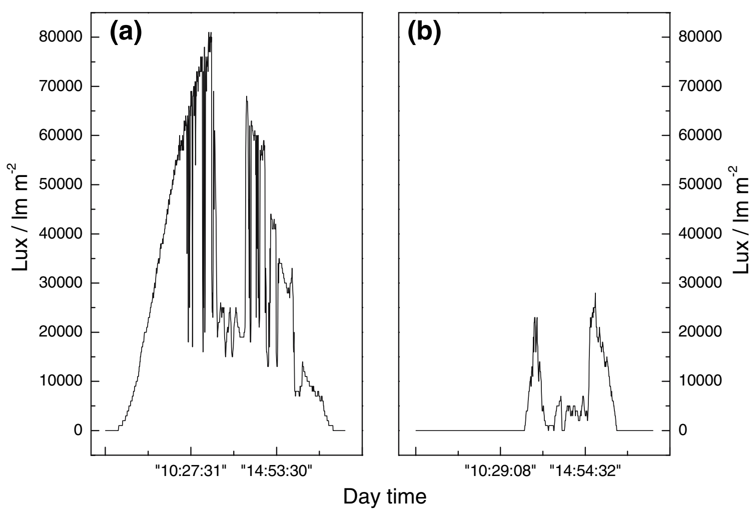


**Fig. 3** Typical lux data on (**a**) a clear day and (**b**) a cloudy day for various type of lead-acid batteries employed during the present solar-lighting application study

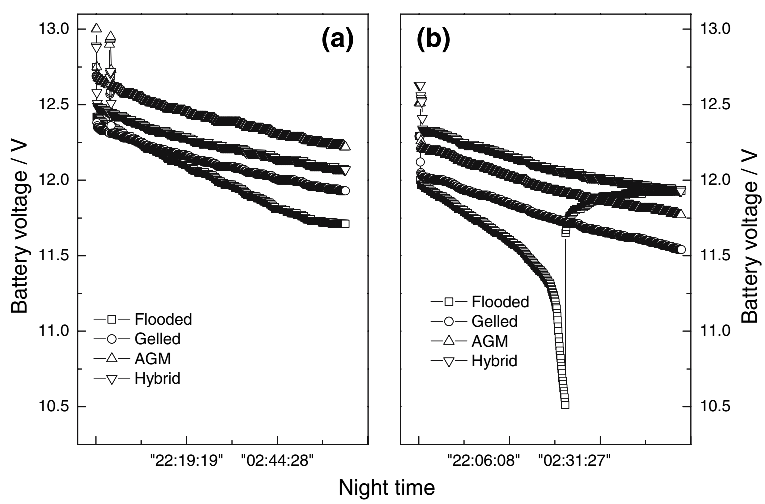


**Fig. 4** Typical discharge data on (**a**) a clear day and (**b**) a cloudy day for various type of lead-acid batteries employed during the present solar-lighting application study

During the field performance test of the batteries for the stand-alone solar-lighting application, end-of-charge (EoC) voltage, end-of-discharge (EoD) voltage data and variation in peak-voltages obtained for hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries for Set I, and Set II are summarized in Table 2. The respective average mean-EoC-voltages for the hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA, and

**Table 2** Variation in average mean-EoC-voltage, mean-EoD-voltage, mean-peak-voltage values and mean-operational voltage-window for hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA, and flooded-electrolyte lead-acid batteries during the present solar-lighting study

| Battery type/ characteristics | Hybrid-VRLA battery | | AGM-VRLA battery | | Gelled-electrolyte VRLA battery | | Flooded-electrolyte lead-acid battery | |
|---|---|---|---|---|---|---|---|---|
| Battery voltage (V) | Set I | Set II | Set I | Set II | Set I | Set II | Set I | Set II |
| Mean-end-of-charge | 12.53 | 12.73 | 12.68 | 12.6 | 12.52 | 12.52 | 12.47 | 12.59 |
| Average mean- end-of-charge | 12.63 | | 12.64 | | 12.52 | | 12.53 | |
| Mean end-of-discharge | 11.83 | 11.96 | 11.96 | 11.83 | 11.67 | 11.70 | 11.21 | 11.36 |
| Average mean-end-of-discharge | 11.90 | | 11.90 | | 11.69 | | 11.28 | |
| Mean-operational voltage-window | 0.70 | 0.77 | 0.72 | 0.77 | 0.85 | 0.82 | 1.26 | 1.23 |
| Average operational voltage-window | 0.735 | | 0.745 | | 0.835 | | 1.245 | |
| Mean-peak voltage | 13.58 | 13.54 | 14.08 | 13.47 | 13.28 | 13.74 | 13.19 | 13.5 |
| Average mean-peak-voltage | 13.56 | | 13.78 | | 13.51 | | 13.35 | |

**Table 3** State-of-health data for hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA, and flooded-electrolyte lead-acid batteries during the present solar-lighting service study

| Battery type | Hybrid-VRLA | | AGM-VRLA | | Gelled-electrolyte VRLA | | Flooded-electrolyte lead-acid | |
|---|---|---|---|---|---|---|---|---|
| Battery capacity (Ah) | Battery Set I | Battery Set II | Battery Set I | Battery Set II | Battery Set I | Battery Set II | Battery Set I | Battery Set II |
| Initial battery capacity | 65.0 | 65.2 | 78.0 | 78.0 | 60.0 | 60.0 | 64.0 | 64.0 |
| Final battery capacity | 24.2 | 22.5 | 26.0 | 25.1 | 21.0 | 20.6 | 8.5 | 8.5 |
| SoH (%) | 37.2 | 34.6 | 33.3 | 32.2 | 35.0 | 34.3 | 13.3 | 13.3 |
| Average SoH (%) | 35.9 | | 32.8 | | 34.7 | | 13.3 | |

flooded-electrolyte lead-acid batteries are 12.63, 12.64, 12.51 and 12.53 V. The respective average mean-EoD-voltages for the hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA, and flooded-electrolyte lead-acid batteries are 11.9, 11.9, 11.69 and 11.28 V. The respective average mean-peak-voltages are 13.56, 13.78, 13.51 and 13.35 V. It is observed during the present study that the average operational voltage-window values, i.e., the difference between EoC and EoD voltages are 0.735, 0.745, 0.835 and 1.245 V, respectively.

As the total panel-impedance values are identical, it is clear that the drop in voltage, i.e., the difference between EoC and EoD voltages, for hybrid-VRLA batteries, is lower than that of the other battery types, which is in conformity with the impedance data [19]. In the literature [20], it is documented that measurements on EoD and EoC voltages provide a useful non-destructive tool to assess the internal resistance of VRLA batteries during their service life. An ideal battery should have a lower voltage operational window for lesser impedance and low peak-voltage for reduced gassing. The hybrid VRLA batteries studied here have the lower operational window and perform better due to enhanced thermal management inside the individual cells. Their charge-acceptance during the service at high temperatures is also better than their AGM counterparts. The higher drop in flooded-electrolyte lead-acid batteries may be due to relatively higher sulfation as no topping-up is done during the study.

During the service of the solar-lighting system, the electrolyte usually increases in concentration, as water is lost from the battery with time, degrading the performance of the battery. In this study, weight loss of water (in %) from the electrolyte is found to be about 1.36%, 1.55%, 2.4% and 13.68% for hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries, respectively. The water-loss data suggest the flooded-electrolyte lead-acid batteries to be inappropriate for any maintenance-free, stand-alone application. SoH values are found to be about 36%, 33%, 35% and 13%, respectively, as shown in Table 3. SoH data clearly suggests that hybrid VRLA batteries are more appropriate than the other three battery types.

While average peak-voltage value for hybrid VRLA batteries are higher in relation to gelled-electrolyte VRLA batteries, the water loss in the hybrid-VRLA batteries is lowest. In practice, both low water-loss and low acid-stratification are desired for any successful SPV lighting application. In the hybrid VRLA batteries, unlike the AGM

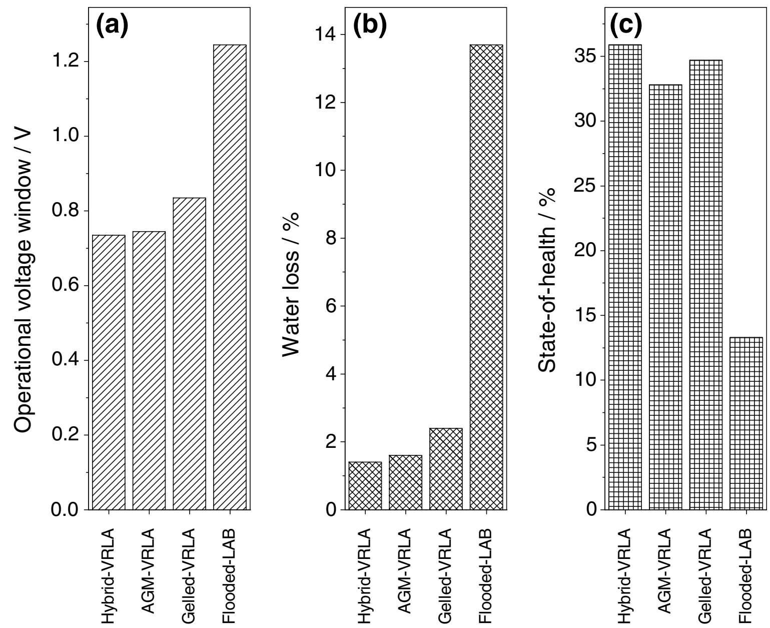


**Fig. 5** A histogram showing (**a**) variation in operational voltage window, (b) water loss and, (**c**) state-of-health data for hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries during the present solar-lighting application study

VRLA batteries [21], the gelled electrolyte helps to mitigate acid stratification. A histogram depicting the variation in operational voltage window, water loss and SoH data for hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA, and flooded-electrolyte lead-acid batteries during the present solar-lighting application study are shown in Fig. 5. However, the present study is just an indicator, as further studies are desired to optimize various battery components and design parameters, which form a part of our on-going R&D program.

## 4 Conclusions

The present field study for PV stand-alone solar-lighting application conducted on hybrid VRLA, AGM VRLA, gelled-electrolyte VRLA and flooded-electrolyte lead-acid batteries suggests that hybrid-VRLA batteries exhibit both lower internal resistance with high thermal stability, which are desirous of a battery for any PV stand-alone application. Among the VRLA-type batteries studied here, water loss for the hybrid VRLA batteries is minimal. Accordingly, hybrid VRLA batteries appear to be most appropriate for PV stand-alone solar-lighting application.

**Acknowledgments** We thank R. A. Mashelkar FRS for encouragement. Financial support from CSIR, New Delhi, is gratefully acknowledged.

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