ELSEVIER

Journal of Power Sources 53 (1995) 255–260

JOURNAL OF POWER SOURCES

Extreme low-maintenance, lead/acid battery for photovoltaic power-supply systems in remote, tropical areas

R.P. Shirodker

United Accumulators Private Limited, Corlim Industrial Estate, Corlim-Goa, India

Received 3 August 1994

Abstract

Thousands of villages in India are still without supplies of mains electricity. Their remote locations make grid connection almost impossible, mainly because of the high costs of transmission. The best alternative is to equip these places with solar photovoltaic systems, and suitable batteries, that will meet the requirements not only for household lighting, televisions and fans, but also for linking the villages with telecommunications systems so that these communities can be brought into development projects. A comparison between nickel/cadmium and both sealed maintenance-free and flooded types of lead/acid batteries has demonstrated the economical and functional superiority of the last-mentioned of the three technologies. A design with very-low-antimony alloys and with a specific cell construction that requires no maintenance over a period of at least one year has been evaluated, especially with respect to water consumption in cycling simulations. The operating conditions relate to solar-powered telecommunications applications. The use of catalytic gas-recombination vent plugs further reduces the maintenance to such a level that the water topping-up frequency is zero during the entire life of the battery.

Keywords: Lead/acid batteries; Photovoltaic power-supply systems; Remote areas

1. Introduction

India lives in villages. Two-thirds of the population is rural and is spread over more than half-a-million settlements. During the past two decades, tremendous strides have been made to provide electric power to about 85% of these villages. Nevertheless, despite such Herculean progress, there are about 90 000 villages yet to enjoy the benefits of electric power. These villages are very remote, inaccessible by road, and situated predominantly in inhospital and mountainous areas. Such conditions are not conducive to the transmission of electricity, nor to the installation of telecommunications facilities.

Despite these difficulties, thirty-thousand remotely located villages, that four years ago had no telecommunications networks, now appear on the telecom map of India. This programme is continuing, and it is envisaged that one million villages will be equipped with telephones within the next two to three years. The feasibility of installing the proposed telephones has been examined in terms of the following two factors:

(i) there are only limited resources to equip the remotely located villages with telephones;

(ii) given both the difficult terrain and the unfavourable economics, it is impossible to consider hard wiring as the means of transmission.

The Department of Telecommunications (DOT) has considered these factors and has decided to provide single-channel VHF radio telephone units, each with a power supply that comprises a 70 W photovoltaic panel and a 12 V, 120 Ah lead/acid battery. Specifications have been set for the battery.

The power source has been sized to operate the equipment at the radio telephone link for a usage of four calls per day, each of 3 min duration. The load schedule is designed to be:

- maximum power consumption: 50 W
- standby-power consumption: 5 W
- nominal operation voltage: 12 V
- ring current: 800 mA per call for 1 min
- current drain by telephone equipment: 180 mA

The single-channel VHF radio telephone operates on an input voltage of 10.8–15 V. Two or three 70 W photovoltaic modules are connected in parallel to charge the 12 V battery bank. The peak power output of the panel is around 15 V and the maximum charging current is 4.7 A.

SSDI 0378-7753(94)01991-4

The battery should possess the following general features:

- high Ah charge–discharge efficiency
- low self-discharge rate
- low maintenance (topping-up frequency of two years)
- sufficient battery capacity for 6–8 consecutive, sunless days
- reliable, safe and robust construction
- low cost

The following three types of battery systems have been considered: (i) pocket plate (flooded electrolyte) nickel/cadmium; (ii) sealed, maintenance-free lead/acid; (iii) low-maintenance, flooded lead/acid. The salient features of each of these systems are given below.

2. Nickel/cadmium, pocket plate (flooded electrolyte)

This battery can be discharged to up to 100% of its rated capacity at the *C*/10 rate. Nickel/cadmium batteries display a life of more than 1100 cycles. Nevertheless, the system suffers from the following drawbacks:

- a high and unavoidable loss of capacity is experienced during storage, e.g., 20% of the rated capacity within 28 days;
- an initial 15 h charging procedure is mandatory (the batteries are supplied in a discharged state), thus, charging facilities must be available, even at remote locations;
- cadmium is an environmentally hazardous element;
- the cost is 4–5 times that of a conventional, flooded, low-maintenance lead/acid battery.

These features preclude the use of nickel/cadmium batteries for cost-effective photovoltaic-based power supplies.

3. Sealed, maintenance-free lead/acid

Lead/acid batteries of either the gelled-electrolyte or absorptive glass-mat type offer prospects as sealed, maintenance-free energy storage units for remote villages in tropical locations. This is due to the following benefits: (i) elimination of the need for frequent addition of water; (ii) flexibility in orientation and installation; (iii) reduction in weight; (iv) leak-proof construction with total elimination of acid mist and spillage. Although extensive research and development is being conducted worldwide in the field of sealed lead/acid batteries, this technology has been found to suffer from the following drawbacks when used in the high-temperature conditions of tropical locations.

- Due to the basically sealed nature, the batteries are sensitive to the operating temperature in that service life is reduced considerably at elevated temperature; this is caused by thermal runaway.
- Overdischarge results in acid starvation, the deposition of lead sulfate within the separators and, ultimately, the development of short-circuits.
- The sealed nature of the batteries eliminates the possibility of determining the state-of-charge by conventional means, i.e., by a hydrometer. Although it is feasible to use conductance measurements to determine the state-of-charge of the battery, the poor correlation between the cell conductance and the residual capacity rules out the practical use of this technique. Furthermore, the cost of the conductance equipment, in addition to the high cost of the batteries themselves, is an inhibiting factor.
- Although the battery is termed 'maintenance-free', manufacturers recommended that the voltage should be checked every two months to confirm the performance level of the battery. Under normal operating conditions, it is also advisable to apply an equalizing charge in order to remove any non-uniformity in the cell charge levels and to return all the cells to the same, fully charged condition.
- There is the major problem of premature capacity loss under deep-cycling duties.

Personnel in remote tropical locations have little technical knowledge and, in the majority of cases, the systems using the above batteries are stand-alone facilities. Hence, the manufacturers' recommendations with respect to regular check-ups and equalizing charging are contrary to the concept of a truly maintenance-free battery as envisaged by the consumers.

4. Low-maintenance, flooded lead/acid

Given the various features and drawbacks of nickel/cadmium and sealed maintenance-free lead/acid batteries (see Table 1 for summary), the only alternative available for a cost-effective and reliable battery for Indian remote-area power-supply applications is the low-maintenance, flooded lead/acid battery. Such a battery has been designed by using the results of earlier research work that has been performed worldwide.

4.1. Design

The battery size calculated for the above application comprised two 3UT 120H units with a nominal voltage of 6 V and a nominal capacity of 120 Ah. The grids were made from a low-antimony (selenium) alloy. The antimony content was around 2 wt.%. This gave a low rate of self-discharge. Selenium was used because of its high grain-refining effect which helps to avoid the embrittlement of grids that is prevalent with low-antimony alloys. This, in turn, increases the corrosion resistance of the grids. Other additives were added in trace amounts, such as arsenic and tin for improvement of grid strength and castability.

Table 1
Comparative performance of battery systems

Feature	Nickel/cadmium	Sealed maintenance-free lead/acid	Low-maintenance flooded lead/acid
Maximum depth-of-discharge	100% of rated capacity	80% of rated capacity	80% of rated capacity
Capacity (C/120 rate)	110% of rated capacity	110% of rated capacity	150% of rated capacity
Life	1100 cycles (minimum)	1100 cycles (maximum)	1100 cycles (minimum)
Capacity loss, 28-day storage	20%	3%	5%
Battery activation at site	battery supplied in discharged state; 15 h (minimum) initial charging required	battery supplied in fully-charged state	battery supplied in dry-charged state; no initial charging required if installed within 6 months
Charging (voltage regulations)	high voltage cut-off mandatory, but low voltage cut-off not necessary	voltage regulation very critical to performance; precise control of charge voltage (e.g., 2.3 V/cell) mandatory	critical factor in battery performance; high/low voltage cut-of required, but less sophistication needed
Maintenance requirements	minimal topping-up	no topping-up; every two months check-up of battery voltage and equalizing charge mandatory	minimal topping up (once a year)
Measurement of state-of-charge	1.6 V/cell for fully charged battery	conductance measurements (inaccurate and costly)	conventional hydrometer and voltage measurements
Reliability	no risk of explosion	risk of explosion due to high ambient temperature and consequent thermal runaway; technology requires improvement	explosion due to thermal runaway not a failure mode; proven technology
Cost	6–8 times more than flooded lead/acid	twice the cost of flooded lead/acid	

Tubular positive and pasted negative plates were used together with low-resistance polyvinyl chloride separators. The cells were assembled in monoblock containers that were made from hard-rubber material. The electrolyte quantity in each cell was such that the level stood at 50 mm above the separator guard.

The terminal posts were connected to the cell lid by welding with a lead bushing provided in the lid. The posts were pressed air tight with the cover so that there was no vertical creepage of electrolyte. Each cell cover was attached to its hard-rubber container by means of an epoxy resin layer so as to provide a leakproof joint after further sealing with bitumen compound. The cells were fitted with flame-resistant, 'Aqua Trap', ceramic vent plugs. These prevented excessive water loss during the gassing periods.

The type 3UT 120H battery was subjected to the following performance evaluation in the laboratory:

(i) capacity tests at the *C*/10 and *C*/120 rates;

(ii) charge-acceptance tests at a constant voltage of 7.35 V;

(iii) water-consumption tests;

(iv) overcharge corrosion tests;

(v) life-cycle test.

4.1.1. Capacity test I

This test was conducted at the *C*/10 rate of discharge and at a current of 12 A. The capacity obtained at 27 °C was 126.98 Ah, see Fig. 1.

4.1.2. Capacity test II

This test was carried out at the *C*/120 rate of discharge and at a current of 1.5 A. The capacity obtained at 27 °C was 182.25 Ah, see Fig. 2.

In order to satisfy the condition of six continuous sunless days (i.e., 6 days of autonomy) under Indian conditions, the capacity obtained at the *C*/120 rate should be at least 150% of the rated capacity, as required by the DOT specifications. The capacity obtained (namely, 182.25 Ah at 27 °C) conformed to these specifications.

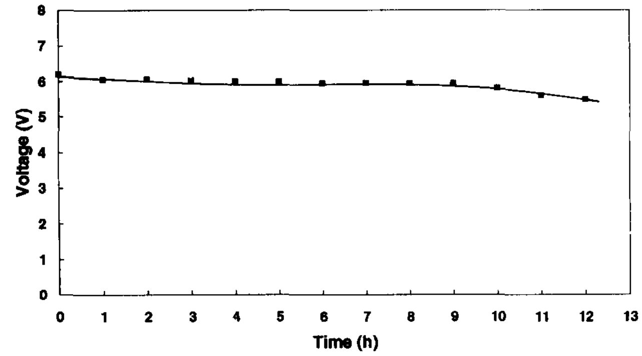

Fig. 1. Capacity performance at *C*/10 rate of 3UT 120H flooded, lead/acid battery. Test temperature: 27 °C.

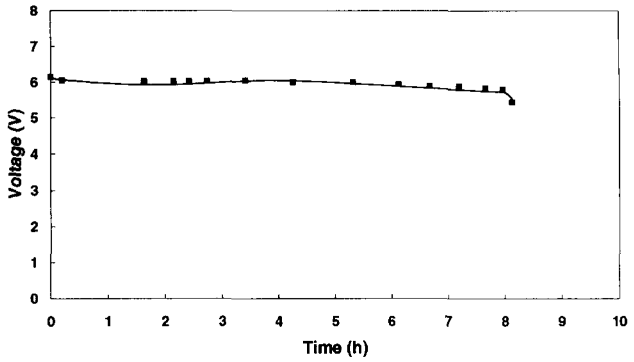

Fig. 2. Capacity performance at *C*/120 rate of 3UT 120H flooded, lead/acid battery. Test temperature: 27 °C.

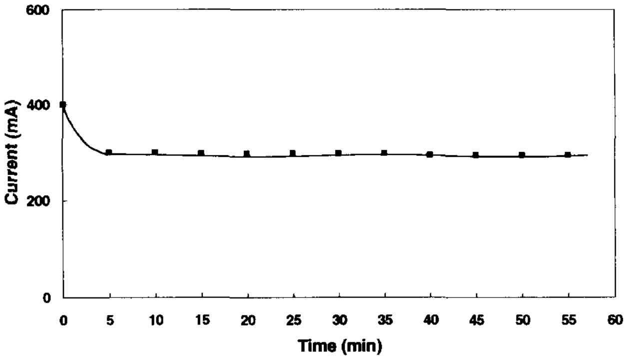

Fig. 3. Charge acceptance of 3UT 120H flooded, lead/acid battery at 2.45 V/cell.

4.1.3. Charge-acceptance test

This test was performed on an initially fully charged battery at a constant voltage of 7.35 V, i.e., 2.45 V/cell. The results are presented in Fig. 3. The overcharge cut-off voltage set on the charge regulator of the power-supply system is 2.45 V/cell as required by DOT specifications. Under such conditions, the charge-acceptance current is found to remain constant at 300 mA, as shown in Fig. 3.

4.1.4. Water-consumption test

The battery was overcharged continuously at a current of 5 A in order to determine the number of hours required for each topping-up period under such conditions. The results are illustrated graphically in Fig. 4. At the end of 200 h of continuous overcharge, the fall in the electrolyte level was 27–28 mm.

This test is not a true simulation of actual field conditions, since it is not envisaged that the battery will be overcharged for such extensive periods in any of the proposed systems. It is evident from extrapolation of the test results that even under such adverse conditions, the battery will not require water replenishment for 15 days.

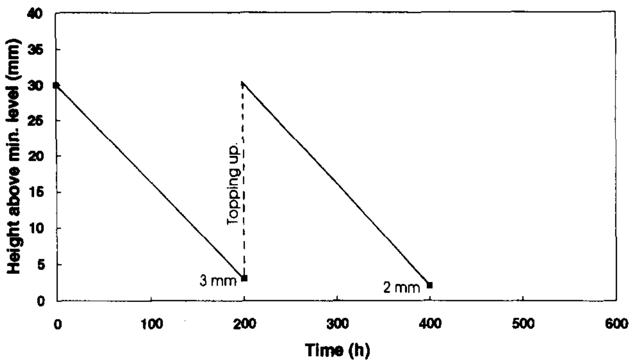

Fig. 4. Water consumption by 3UT 120H flooded, lead/acid battery at an overcharge current of 5 A.

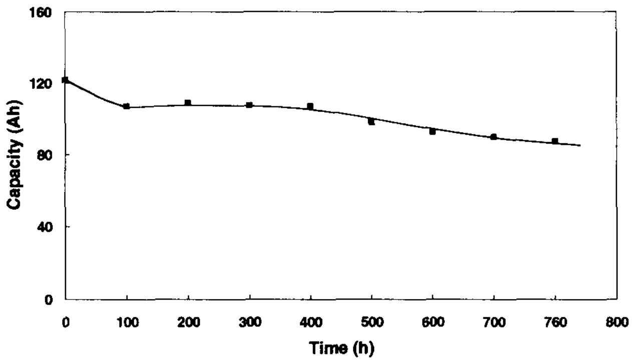

Fig. 5. Overcharge (corrosion) performance of 3UT 120H flooded, lead/acid battery. Overcharge current: 5 A.

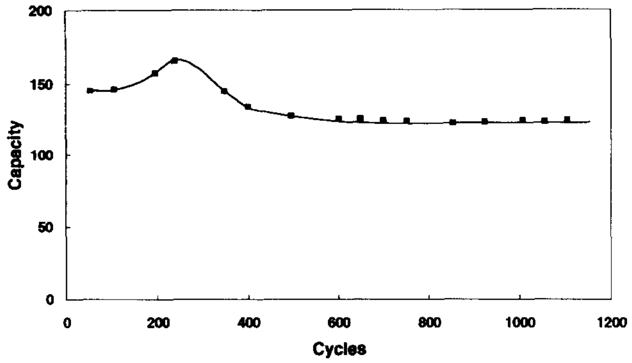

Fig. 6. Life performance of 3UT 120H flooded, lead/acid battery. Depth-of-discharge: 25%.

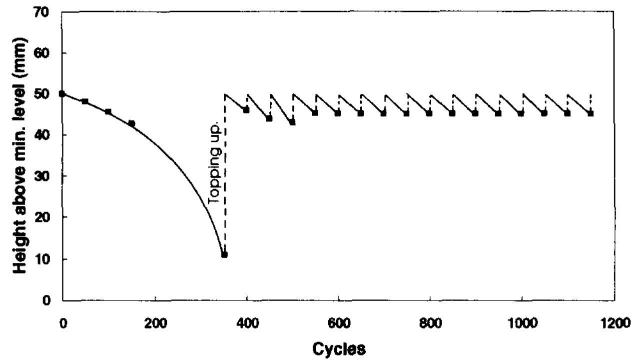

Fig. 7. Water consumption by 3UT 120H flooded, lead/acid battery during life-cycle test.

4.1.5. Overcharge corrosion test

The battery was subjected to an overcharge corrosion test via the following procedure: (i) continuous overcharge for 100 h at 5 A; (ii) rest for 12 h; (iii) capacity test at *C*/10 rate; (iv) repeat of sequence (i) to (iii). The experimental results are presented in Fig. 5.

4.1.6. Life-cycle test

In the life-cycle test, the battery was subjected to: (i) 3 h discharge at 9.9 A; (ii) 5 h charge at 6.6 A. The temperature was held at 40±2 °C. At the end of every 50 cycles, a capacity test was performed at the *C*/10 rate. No addition of water was required during the first 350 cycles. Thereafter, a fall in the water level was noted at the end of each successive set of 50 cycles. The cells were repeatedly topped up to the set level, i.e., 50 mm above the separator guard. The life-cycle test was continued until the capacity was less than 80% of the nominal value.

The capacity performance and the consumption of water at intervals of 50 cycles are displayed in Figs. 6 and 7, respectively. It is to be noted that at the end of 350 cycles, the cell was replenished when the level had dropped by 38 mm, i.e., 12 mm above the separator guard. Nevertheless, extrapolation of the water-consumption curve indicates that the life-cycle test could have been continued for up to 460 cycles without the need for water addition to the cell (i.e., by virtue of the remaining 12 mm of electrolyte). Hence, it can be concluded that this low-maintenance battery (type 3UT 120H) would require no water maintenance for at least one year.

The life-performance data (Fig. 6) demonstrate that after 1100 cycles the capacity of the battery remained at the 100% level. The test is still in progress and, given the present trend, the battery is expected to last for at least 7000–8000 cycles at 25% depth-of-discharge before its capacity falls to below 80% of the nominal value.

5. Extremely low-maintenance, flooded lead/acid

In order to incorporate totally maintenance-free characteristics in the 3UT 120H type of lead/acid battery, the cells were fitted with gas-recombination ('recombinant') catalytic vent plugs that are manufactured by Accumulatorenwerke Hoppecke, Brilon, Germany. These plugs use a platinum catalyst on a alumina/silica carrier to recombine the hydrogen and oxygen gases that are evolved during overcharging. Water vapour is formed initially which then condenses to water that subsequently returns to the cell. Care is taken to avoid poisoning of the catalyst by stibine (SbH_3) and arsine

(AsH_3). This is achieved because the grid alloys contain a low content of antimony, i.e., the concentration of stibine gas generated is well below the threshold limit that would cause poisoning of the catalyst.

The vent plugs were fitted to the cell so that there was no leakage of gases. Finally, it is recommended that, when installed at the site, the battery along with the power-supply system should be protected from direct sunlight and an appropriate protective shade/enclosure should be provided.

5.1. Water consumption test

The battery was continuously overcharged at a current of 5 A to determine the number of hours that was required for each topping-up period under such conditions. The results are given in Fig. 8. At the end of 200 h of continuous overcharge, the electrolyte level had fallen by only 1 mm. By comparison, the low-maintenance battery without catalytic vent plugs registered a drop in electrolyte level of 27–28 mm. Thus, there is a marked improvement in performance with the modified design. From extrapolation of the data, it can be concluded that, for an overcharge of 5 A, the battery requires no water addition for a period of at least 7 months. It should be noted that such severe overcharge conditions will not be encountered in actual field service.

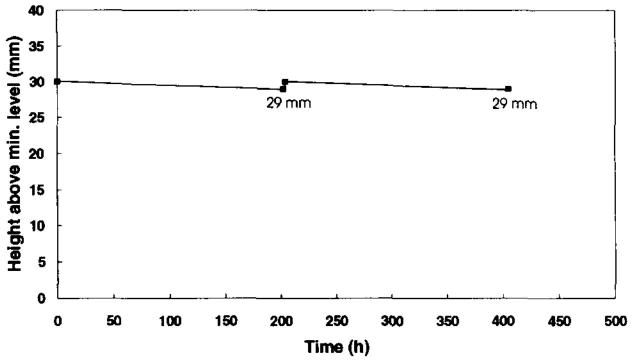

Fig. 8. Water consumption by 3UT 120H flooded, lead/acid battery at an overcharge current of 5 A. Cells fitted with catalytic recombinant vent plugs.

6. Conclusions

It has been determined that the maximum charge-acceptance current for a fully charged 3UT 120H type of flooded lead/acid battery at a constant voltage of 2.45 V/cell is 300 mA. This is negligible compared with the 5 A current with which such a battery fitted with catalytic recombinant vent plugs ('extreme low-maintenance' version) was overcharged. The extreme low-maintenance battery requires a topping-up frequency of 7 months when continuously overcharged at 5 A. Thus, it can be concluded that for an overcharge current of 300 mA the topping-up frequency will be extended to the lifetime of the battery, i.e., 7 to 8 years. It should be emphasized, however, that such a condition of continuous overcharge at 300 mA is unlikely to be experienced in actual field service where, in practice, the battery would be subjected to daily cycling with a minimum overcharge period.

Hence, it can be confidently concluded that the extremely low-maintenance, flooded lead/acid battery fitted with catalytic recombinant vent plugs would require no water additions throughout its lifetime, provided the system to which it is connected has an appropriate charge regulator. For this reason, the battery is the most appropriate unit for use in photovoltaic-based power supplies for Indian villages in remote and tropical locations.