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RECOMMENDATIONS FOR MAXIMIZING BATTERY LIFE IN PHOTOVOLTAIC SYSTEMS: A REVIEW OF LESSONS LEARNED

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ABSTRACT

This report contains notes, observations and recommendations about the use of batteries in small stand-alone photovoltaic (PV) systems. The conclusions of this work are based on the results of more than a decade's worth of battery testing at the Florida Solar Energy Center and related work with Sandia National Laboratories, the PV industry and user groups. The most critical findings were the relationship between battery state-of-charge and battery life and the importance of an adequate PV array-to-load ratio.

INTRODUCTION

The information presented herein is principally intended for those involved with the design, installation and maintenance of small PV systems. Specific results from component testing and system evaluations have been condensed into general categories of importance, including issues related to battery type, system sizing, charge control, and system installation, operation and maintenance. This is not a design guide or tutorial on batteries in PV systems, and assumes the reader has a fundamental understanding of PV systems and how their individual components interact in an operating environment. The results primarily correlate to flat-plate flooded lead-acid and valve-regulated lead-acid (VRLA) batteries commonly used in small photovoltaic systems, and represent the best understanding of current technology.

NOMENCLATURE

A:L Ratio - Array to Load Energy Ratio
ARV – Array Reconnect Voltage
CRC - Catalytic Recombination Caps
LRV – Load Reconnect Voltage
LVD – Low Voltage Disconnect
PWM – Pulse Width Modulation
SOC – State of Charge
V_{oc} – Open-Circuit Voltage
VR – Voltage Regulation
VRLA - Valve-Regulated Lead-Acid

WHY THIS REPORT WAS WRITTEN

Numerous problems may arise in stand-alone PV systems. Premature battery failure is among the most common, and is a major concern throughout the PV industry and user groups. Although they are a relatively low fraction of a system's initial costs, batteries can be the most expensive component in the overall life cycle cost of stand-alone PV systems.

Batteries are the heart of any small PV system. More often than not, any problem associated with these systems manifests itself in an apparent problem with the battery, whether the battery is at fault or not. Oftentimes factors such as insufficient system sizing, component reliability, or improper installation, operation and maintenance practices are to blame.

There are several tradeoffs in designing small stand-alone PV systems. Due to the high initial cost of PV systems, emphasis is often placed on minimizing initial costs at the expense of higher life cycle operating and maintenance costs. In other cases, where the critical nature of the application warrants conservative design practices, higher initial costs hopefully translate into lower life cycle costs. Generally, battery life cycle performance and load availability are inversely related in small PV systems; as the charge control setpoints are altered to allow more energy to be withdrawn from the battery, the battery life becomes more limited. In other words, increasing load availability for a given design through lower load control set points usually decreases battery life, while increasing load control set points to improve battery health usually compromises load availability. These tradeoffs have consequences for both the system designer and user alike.

Due to the variability in solar radiation, and the uncertainty in electrical load profiles, some loss of load can usually be expected in any small stand-alone PV system. While increasing battery and/or PV array size can reduce loss of load probability, there are practical and economic limits to how conservative a system should be sized. Theoretically speaking, increasing battery size should give a proportional increase in cycle life for a

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given load profile. However this is not necessarily the case for small PV systems. Although increasing battery size may result in a greater autonomy period, lower charge/discharge rates and a shallower daily depth-of-discharge also increases the recovery time from low battery state-of-charge.

This report summarizes what we have found throughout our years of testing and dealing with these and other issues associated with battery use in PV systems. We hope the lessons learned from these experiences will be used to help improve the design, performance and reliability of small stand-alone PV systems.

OVERVIEW OF LESSONS LEARNED

1. Issues Related to Battery Types and Characteristics

Three types of lead-acid batteries are typically used in small stand-alone PV systems, and are differentiated by the form of their electrolyte. These types include flooded lead-acid, gelled electrolyte, and absorbed glass mat (AGM). The latter two are commonly referred to as sealed or valve-regulated lead-acid (VRLA) type batteries [1]. This is because they are designed to not need additional water over the lifetime of the battery. Valves are installed in each cell to prevent gas build up within the sealed batteries. Excessive overcharging causes increased gassing, and is extremely detrimental to these types of batteries because water cannot be added to replace what is lost during gassing.

Alkaline batteries such as nickel-cadmium and nickel-metal-hydride are sometime used in critical and extreme temperature applications [2]. However, their lack of availability in many areas and high initial cost limits their application in most small PV systems.

Although more expensive than comparable flooded lead-acid batteries, VRLA batteries are now used in a majority of small PV systems due to their low maintenance requirements. In our tests, gelled electrolyte batteries generally performed better than comparable AGM batteries in small stand-alone PV systems, which is consistent with the expectations of two major U.S. manufacturers of both gelled and AGM batteries (though, this is not always the case) [3]. Similarly rated batteries produced by different manufacturers may have significantly different levels of success in PV applications.

Due to their sealed construction, electrolyte can not be added to VRLA batteries. For this reason, these batteries are extremely intolerant of high temperatures and overcharging. A common problem for these batteries in PV systems ten years ago was that the electrolyte dried out. This has been largely eliminated by improvements in VRLA technology and the use of better charge control and lower regulation voltages.

In general, battery cycle life is related to its average depth-of-discharge as long as it is charged properly, not severely over-discharged, or operated at high temperatures. The preferred battery failure mode in PV systems is positive grid/plate corrosion, which occurs from typical use under optimal conditions. Failure from sulfation and stratification indicate insufficient battery charging. This occurs when the state-of-charge is kept low, and may result if the array is too small and can not generate enough electricity to return the batteries to full capacity within one to three days, depending upon the solar resource [4].

Certain battery design and construction features can enhance long-term battery performance in PV systems and other deep cycling applications. The features include reserve electrolyte volume, extra mud space beneath the plates, envelope plate separators to contain shed material and prevent short-circuiting, and accessibility for visual inspection and electrolyte maintenance.

Alloying elements in the grids of pasted flat-plate lead-acid batteries provide mechanical strength to the grid and have certain effects on battery performance. In general, flooded lead-acid batteries that perform well under deep cycling applications have thick plates (>20 mm) and between 3 and 6 percent antimony content in the positive plate [5]. While lead-antimony designs have high water loss and self-discharge rates, they perform well under high temperature, low discharge rates and deep discharge conditions. Calcium is alloyed with lead to form the grids for most VRLA batteries and results in substantially lower gassing and self-discharge than flooded lead-antimony batteries. However, they do not perform as well as lead-antimony designs under high temperature and deep discharge conditions.

Electrolyte concentrations for flooded lead-acid batteries should be adjusted based on the climate. Nominal specific gravity is 1.28. In cold climates, specific gravities of 1.30 or higher may be used to prevent freezing at low state-of-charge and attain higher capacity. In warm climates, specific gravities as low as 1.19 have been used to improve cycle life, and limit electrolyte loss, grid corrosion and self-discharge [1].

Although battery manufacturers often provide cycle-life expectations as a function of depth-of-discharge, this information is seldom applicable to the unique battery operational profiles in PV systems. This has made battery cycle life in PV systems extremely difficult to predict. As a result of our work and growth of the PV-battery market, some battery manufacturers are now providing better information and guidelines specifically for PV applications [1].

2. Issues Related to System Sizing

The array to load energy ratio (A:L) is perhaps the most important parameter in sizing stand-alone PV systems with energy storage, and it has significant effects on battery health and load availability. The A:L ratio represents the average daily amount of energy that can be output by the array divided by the average daily load usage during the critical design period (month with lowest insolation to load ratio).

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Array to load energy ratios of 1.1 have long been considered adequate, but in most cases a minimum A:L ratio of 1.3 is required in a clear climate to maintain battery state-of-charge in small PV systems [6]. Test results indicate that batteries cycled in PV systems with an A:L ratio of 1.1 yielded between one-half and one-quarter as many cycles as batteries operated at A:L ratios of 1.3 and higher [7]. A:L ratios greater than 1.3 may be necessary depending on climate, system inefficiencies, and battery self-discharge rates.

The A:L ratio also determines the number of cycles one may reasonably expect from a battery and how quickly a battery can recover full state-of-charge from a deficit condition. In typical systems with five days of autonomy, a month or more may be needed to recover full battery state-of-charge from a low-voltage disconnect condition with normal load usage.

Problems associated with the reliability of load equipment (variability in operating current) or excessive or uncontrolled load usage by the system operator may lower the A:L ratio and jeopardize battery health.

Battery sizing must take into account the minimum and maximum temperatures expected for the installation. Available capacity is significantly reduced at low temperatures, and particularly at higher discharge rates [8]. In addition, depth-of-discharge must be limited to prevent the electrolyte from becoming diluted enough to freeze. Since low temperatures are often coincidental with periods of low insolation, this places an exceptional burden on the battery. In high temperature applications, battery cycle life expectations must be correspondingly reduced.

3. Issues Related to Installation, Operation and Maintenance

3.1 Installation Issues

The state-of-charge of batteries received from manufacturers for testing varied between 50 and 90 percent [9, 10, 11]. Due to a higher self-discharge rate, flooded lead-antimony batteries were typically at lower state-of-charge upon receipt than VRLA batteries [10].

Installation of partially charged batteries in PV systems may adversely affect system operational performance, particularly if installed during a critical design period with low insolation and high load. Battery state-of-charge should always be assessed before installation in PV systems. If the necessary charging cannot be performed prior to installation, the system should be operated without the load until the batteries have been completely recharged.

3.2 Operational Issues

Battery capacity is dependent on several operational factors, including discharge rate, depth-of-discharge, temperature, and age. High discharge rates, limited depth-of-discharge, and low operating temperatures all reduce available battery capacity.

Because the capacity of lead-acid batteries is significantly affected by temperature, batteries should be protected from temperature extremes. While battery life is generally reduced by 50 percent for every 10^{o}C increase in average operating temperature, battery capacity is reduced at lower operating temperatures [8]. Optimal temperatures for battery storage are near 25°C.

Buried battery boxes allow the soil to act as insulation, and thermally regulated enclosures can significantly limit battery temperature swings. Buried battery boxes should be water-tight, though boxes should be elevated in wet climates. The top and sides of buried battery boxes should always be sealed. Depending upon the level of the water table, holes may be used at the bottom of the box to allow for drainage of any water collected [12, 13].

Excessive system voltage drops due to wiring, diodes, fuses and terminations can adversely affect battery performance in small PV systems by limiting the array's charge current and the ability of charge controllers to effectively manage battery state-of-charge. Voltage drop from the controller to the battery lowers the actual regulation voltage seen at the battery terminals. Voltage drop between the controller and load increases the effective low voltage load disconnect point at the battery terminals, potentially causing premature load shedding. Good wiring practices and the use of battery voltage sense leads on controllers that allow the controller to gauge the battery voltage can eliminate many of these concerns.

In applications where the load can be manually controlled, excessive use of the system load should be limited during periods of below average insolation to maintain high battery state-of-charge. For example, ice-making in vaccine refrigeration systems or the use of non-critical loads in solar home systems should be limited during times of low state-of-charge.

3.3 Maintenance Issues

Specific gravity is a key to the health of flooded lead-acid batteries. Specific gravity measurements that are consistent and high indicate a healthy battery, while inconsistent and low readings indicate potential undercharging and/or the need for battery equalization [10, 11].

For VRLA batteries, conductance readings may be useful in field assessments. Conductance measurements (the reciprocal of resistance) are taken between the positive and negative battery terminal, and are an indicator of the battery's ability to hold a charge. The higher the conductance, the lower the likelihood a battery can maintain a charge [10].

Gassing and water loss for flooded lead-acid batteries increases with higher charge voltages and higher operating temperatures [9]. Seasonal temperature changes can affect battery water loss rates by a factor of two or three in small PV systems. Batteries that have excess reserve electrolyte volume

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above the plates can help reduce the frequency for needed water additions.

Catalytic recombination caps (CRCs) reduced battery water loss by more than a factor of two in the flooded lead-acid batteries tested [1, 6, 14]. No measurable differences in battery water consumption were observed between the on-off and constant-voltage controllers when testing batteries with CRCs. Given the cost considerations, CRCs are most appropriate in situations where flooded batteries are used in remote systems that are difficult to maintain.

CRCs become warm when a battery cell approaches full state-of-charge. Along with specific gravity readings, this feature can be used in the field to determine the relative consistency and charge condition of each cell in the battery. If significant temperature differences exist between the CRCs, the battery may be in need of an equalization charge.

CRCs are generally not suited for batteries receiving frequent and automated equalization charges [6]. Increased gassing can result in high CRC temperatures, causing the caps to melt. Sometimes CRCs may become “wetted” – a process in which they become less effective due to saturation of the catalyst. Warming CRCs in an oven can sometimes recondition them.

Based on capacity tests conducted on flooded lead-antimony batteries, an empirical formula was derived to estimate state-of-charge (SOC) in nominal 12-volt systems [15]:

$$\text{SOC}\,(\%) = (V_{oc} - 11.46) * 71 \qquad (1)$$

where V_{oc} is the open circuit voltage of the battery. This formula can be used in place of counting ampere-hours, and hence is not affected by the changing capacity throughout the battery’s life. This formula is only valid if individual cells have not failed. The V_{oc} measurements to determine SOC should be taken when there is no charge or discharge current, the battery is near room temperature and the battery’s electrolyte has had time to reach equilibrium (several hours).

4. Issues Related to Battery Charge Control

Charge controllers play a key role in properly managing battery state-of-charge in small PV systems. In addition to providing overcharge protection for the battery, most charge controllers provide load control functions to prevent battery over-discharge. Although a wide variation exists in the types, set points and features of commonly available battery charge controllers, there are generally optimal (or preferred) control characteristics for specific types of batteries and system configurations.

The following section describes our principal findings and recommendations about battery charge control in small PV systems.

4.1 Types of Charge Controllers

Most charge controllers in small PV systems use battery voltage set points for regulating the charge and discharge of the battery. A few controllers use ampere-hour tracking, and recent microprocessor developments have allowed for more complex algorithms to better manage the battery under the variable operating conditions found in PV systems.

Controllers are often classified according to their charge regulation algorithm. The principal methods to regulate voltage used in small PV systems include simple on-off (interrupting), linear constant-voltage, and high-frequency pulse width modification (PWM). Switching elements are typically MOSFETs or similar power switching device. Since PV arrays are current limited, battery charge can be regulated by either short-circuiting the array (shunt controller) or by open-circuiting the array connection to the battery (series controller).

While early PV controllers experienced a variety of safety and reliability problems, with few exceptions these problems have been addressed by manufacturer’s product developments. Several controllers are now listed with Underwriter’s Laboratory and other organizations.

AC ripple from motor loads (water pumps, refrigeration compressors, etc.) can affect the proper operation of some controllers by falsely triggering control set points. Controllers used in these types of applications should be able to accurately determine battery voltage and make appropriate control decisions [15].

4.2 Voltage Regulation and Charge Acceptance

For common voltage-based battery charge controllers, the voltage regulation set point (VR) is the highest voltage that the controller allows a battery to reach in operation at a given temperature. For simple on-off controllers, the array is disconnected from the battery at the VR set point and remains disconnected until the battery voltage drops to the controller array reconnect voltage (ARV). For PWM and constant-voltage controllers, the array current is limited once the VR set point is reached while maintaining the battery at the VR set point provided that enough current is available from the PV array.

Optimal charge regulation voltages in PV systems are dependent not only on the type of battery, but also on system operating parameters (e.g. charge and discharge characteristics) and the controller algorithm.

Due to the limited time available to recharge batteries in PV systems (during peak sunlight hours, or usually 9:00 am to 3:00 pm), the necessary battery charge regulation voltages are higher than what battery manufacturers typically recommend for ‘float’ applications (e.g. UPS systems). Some battery manufacturers now provide recommended charge regulation voltages for their batteries in PV systems.

A certain amount of overcharge is required to maintain battery state-of-charge in PV systems. The proper charge regulation voltage is key to maintaining adequate charge

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without excessive overcharging. For flooded lead-acid batteries, overcharge requirements are typically 120 to 130 percent of full capacity. For VRLA batteries, overcharge requirements are somewhat lower, between 105 and 110 percent [2, 10, 16].

The charge acceptance, or ability to receive and store energy from a charge, is dependent on the rate and depth of the preceding discharge for all batteries. In general, higher charge acceptance is associated with low-rate discharges. Battery charge acceptance is greatest when the battery is not close to full state-of-charge [10, 11].

For some batteries tested at low charge rates and high regulation voltages, over 90 percent of the total charge acceptance was received by the time regulation voltage was reached. At higher charge rates, the charge acceptance by regulation was typically lower than 80 percent, requiring a longer float period to fully recharge [12].

Higher VRs resulted in greater charge acceptance for most flooded lead-acid batteries. However, this comes at the expense of greater water loss and increased maintenance. Regulation voltages that are too high accelerate grid corrosion and lead to pre-mature battery failure.

Increasing the regulation set point and overcharge for some VRLA batteries did not significantly improve the ability of the battery to recharge in a certain time period. This is due to the rapid increase in voltage as VRLA batteries reach full state-of-charge. These types of batteries often require long “float” periods to fully charge.

For simple on-off controllers, the difference between the VR and ARV (often called the voltage regulation hysteresis, or VRH) is an important control parameter. This value must not be so large that the array remains disconnected for extended periods after the VR is reached. Based on our testing, acceptable ranges for the VRH vary between 0.6 and 1.0 volt for nominal 12-volt systems. This VRH is proportional to the battery’s nominal voltage (e.g. 1.2 volts and 2.0 volts for a 24-volt system).

For typical flooded lead-antimony batteries tested, a constant-voltage VR of 2.4 volts per cell (VPC) maintained at least 90 percent of their initial capacity after one year [14]. Similar results were found for on-off controllers with a charge regulation voltage of 2.45 VPC (14.7 volts) and an array reconnect voltage of 2.28 VPC (13.7 volts) [6]. This hysteresis between the regulation and reconnect voltages for on-off controllers is critical to maintaining battery state-of-charge and ensuring that enough overcharge is provided to flooded lead-antimony batteries after initial voltage regulation. A lower array reconnect voltage would not have provided the overcharge needed for these batteries.

Experiments have led FSEC to the following suggested VR voltage recommendations for PV batteries [5]. Note that the values listed in Table 1 are merely guidelines and may vary based on the particular battery model and manufacturer.

Test results have shown that temperature compensation of the VR set point is important in maintaining battery state-of-charge during cold conditions and helps reduce water loss and grid corrosion during warm conditions. Recommended values for temperature compensation coefficients range from –4 to –6 mV/°C/cell for lead-acid batteries [1, 2]. Again, optimal temperature is in the vicinity of 25 °C.

The temperature of the charge controller may not be representative of the battery temperature because of internal heating from the charge controller [6]. Therefore, if temperature compensation is to be used, it should monitor battery temperature at the battery or ambient temperature, not the internal charge controller temperature.

Table 1. Recommended Battery Charge Regulation

	Battery Type			
Regulation Voltage for Nominal 12 Volt Battery at 25°C	**Flooded Lead-Antimony**	**Flooded Lead-Calcium**	**VRLA - Gel**	**VRLA - AGM**
Constant Voltage (PWM)	**14.4-14.8**	**14.0-14.4**	**14.0-14.2**	**14.1-14.4**

Set Points for PWM Charge Controllers [1, 8]

4.3 Low Voltage Load Disconnect

The controller’s low voltage disconnect (LVD) set point protects the battery from over-discharge by shedding the load. It is the lowest voltage that a controller allows a battery to reach, and at given discharge rates, defines the maximum allowable battery depth-of-discharge. The load reconnect voltage (LRV) is the set point at which to load is allowed to draw current from the battery. These set points play a major role in how a battery is treated in small PV systems, and load availability.

For a given design, lower load disconnect set points result in better load availability in the short term at the expense of maintaining high battery state-of-charge. Conversely, higher load disconnect set points help maintain battery state-of-charge while compromising load availability.

Typical LVD set points of charge controllers in small PV systems range from 10.8 to 12.0 volts for nominal 12-volt systems [5]. Tests using discharge rates common in small PV systems indicate that this LVD range does not guarantee a high state-of-charge. In fact, the SOC in these tests varied between zero and 100 percent. A typical LVD set point of 11.5 volts was used in some tests. Our test results indicated battery depth-of-discharge varied between 75 and 85 percent for various batteries tested [1, 10]. Furthermore, at a given discharge voltage, batteries that are undercharged or failing are typically at a greater depth-of-discharge than healthy batteries.

The LRV should be high enough to allow the battery to recharge enough after an LVD event such that when the load is reconnected, the battery is not immediately drawn back down to LVD. Common controller LRV values for nominal 12-volt systems range from 12.0 to 13.0 volts, which results in a wide range of charge recovery before the load is allowed to reconnect. Our tests showed that gelled batteries received very little charge by the time they reached 12.3 volts, and only 25 percent state-of-charge was reached for AGM types at this voltage [3]. This situation can also cause batteries to remain at low state-of-charge for extended periods in systems with marginal A:L ratios.

SUMMARY

- Maintaining high average state-of-charge is critical to maintaining expected battery performance and cycle life in small PV systems.
- Systems should be sized with an array to load (A:L) ratio of at least 1.3 during the critical design period to ensure that adequate energy will be available from the array to recharge the battery.
- The magnitude and duration of the electrical load must be carefully evaluated and periodically checked. Systems in which the user manually operates the load are more prone to battery problems than systems with automated load operation. Special precautions, including higher LVD set points, should be considered in such applications.
- Charge controller set points should be specified based on the type of battery used, the controller algorithm, and system operation characteristics. If the appropriate set points are used, batteries in small PV systems can be treated equally as well with either interrupting, constant-voltage and PWM controllers (see Table 1).
- Temperature compensation of the VR set points should be employed whenever possible, especially when VRLA batteries are used. Furthermore, this temperature should be measured at the battery, external to the charge controller.
- Catalytic recombination caps (CRCs) can substantially reduce water loss for flooded lead-acid batteries. Battery manufacturers should be consulted about using CRCs supplied from another source.

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