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Rating Batteries for Initial Capacity, Charging Parameters and Cycle Life in the Photovoltaic Application

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Abstract

Stand-alone photovoltaic (PV) systems typically depend on battery storage to supply power to the load when there is cloudy weather or no sun. Reliable operation of the load is often dependent on battery performance. This paper presents test procedures for lead-acid batteries which identify initial battery preparation, battery capacity after preparation, charge regulation set-points, and cycle life based on the operational characteristics of PV systems.

Introduction

Photovoltaic (PV) systems generate electricity from the sun and may power diverse loads from a fraction of a watt to kilowatts. A typical stand-alone PV system will store the energy in batteries to power the load at night or during periods of minimal sun. Many of the cost effective applications for PV are in remote, environmentally harsh conditions. PV systems are also subject to seasonal changes in temperature and battery charging (dependent on solar resource). Traditionally PV system designers have had to draw on battery operating parameters from other applications such as motive or standby power systems. These applications have significantly different operational characteristics than PV systems.

PV system designers and installers have reported that batteries in PV systems typically fall short of expectations (capacity, cycle life, etc.) when design parameters are used from other applications [1-5]. This may not be a problem with the battery itself, more likely, it is a problem with expectations and performance data used. Obtaining the optimum cycle life vs. cost and maintenance is the ultimate objective and requires reliable battery performance data for the application [6]. There is also a general lack of readily available information on how to charge and operate batteries in PV systems based on responses from a 1992 survey [7] and experience at the Photovoltaic Design Assistance Center at Sandia National Laboratories, Albuquerque, New Mexico.

Establishing the Test Procedures

Experience and testing efforts regarding the use of batteries in photovoltaic systems at Sandia have shown the need to develop a process for characterizing batteries specifically for the PV application [8-11]. Sandia has begun an effort to establish a set of documented procedures to develop operating parameters for lead-acid batteries as they are used in PV systems. The procedures are for: 1) initialization of the battery, 2) determining appropriate battery capacity, 3) charge regulation set-points, and 4) cycle lifetime. While providing a guide for the initial specifications, these procedures will also allow variations in operational parameters, system design philosophies and charge controller products.

The information presented here is that of a working document, with procedures still under development. When the procedures are finalized any battery may be characterized for use in PV systems, thereby, excluding no battery or manufacturer from participating in this expanding market (25% growth/year [7]). The tests may use a single set of parameters determined by the investigator (depth-of-discharge, charge rate, charge method, etc.) or variations of those parameters. Final determination of acceptability of capacity or cycle lifetime are dependent on the designer's decision based on results obtained.

By following these procedures, the PV application specific battery specifications will allow PV system designers to compare operating performance of

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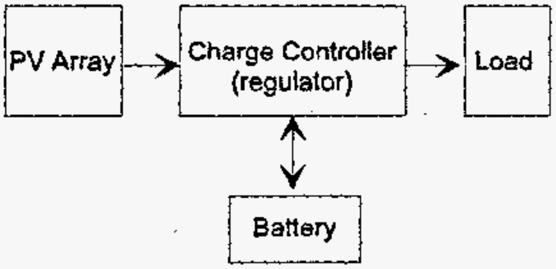
virtually any battery under circumstances more closely related to actual PV operating characteristics. This will reduce PV system costs associated with guesswork on battery specifications and increase system reliability by the use of more accurate operating characteristics.

The Photovoltaic Application

Stand-alone PV systems are generally comprised of a PV array, system/charge controller, battery storage, and a load (device to be powered) as shown in Figure 1 [13]. The PV array generates current dependent on the intensity of the sun. Operating voltage is dependent on the internal resistance of the PV array (power source) and the battery state-of-charge. Generally speaking, the PV array may be considered a current device. Due to seasonal variations, PV system designers will design their system with the solar resource at the site based on the worst case scenario (low solar resource periods). As the seasons change, there will be an excess of power generated during peak solar resource periods and limitation of overcharging will be required.

Figure 1, Basic PV System



Therefore, when charging a battery in a PV system a voltage regulator, sometimes referred to as a charge controller, is typically used to limit battery voltage during the finishing charge. Limiting this overcharge is vital to the life of the battery and controlling maintenance intervals for battery watering [8]. Extending battery life and minimizing battery maintenance in remote applications is necessary due to the high cost of visiting remote sites (i.e. $100's to $1,000's per visit).

PV System Operating Parameters

Seasonal variations in solar resource (charging) and temperature introduce significant variations from traditional battery recharge regimes. Motive power specialists may base cycle life on the anticipation of consistent deep cycling and full recharging. UPS specialists design for extended periods of float charging and occasional deep cycles, with immediate full recharge following a deep-cycle. These are the two applications that PV systems designers draw most of their operating parameters from. Both of these applications are typically in controlled environments with established, predictable discharge and recharge scenarios.

The PV system designer typically considers cycle life vs. depth-of-discharge, percent of available overcharge available after each daily cycle, and seasonal temperature variations when designing the system. Cycle life is directly affected by all of these parameters. To ensure system reliability (battery capable of sustaining the load) a better understanding of how much these factors affect cycle life is required.

Characteristics and Parameters Developed Through Testing

To develop an understanding of how a battery will function in a PV system, the fundamental variables experienced in PV systems need to be examined. After gathering a functional knowledge base on how these characteristics are affected by the operating parameters, use of batteries in PV systems becomes more reliable and effective.

Characteristics & parameters to be examined:

- *Initialization of the battery*
- *Initial capacity & system operating capacity*
- *Charge acceptance*
- *Percent of overcharge required daily*
- *Voltage regulation (charge control)*
- *Cycle life*

Initialization of the Battery

How a battery is prepared for service is important to what the initial capacity will be and how the battery will perform once installed. Unlike motive applications, where initial deep cycles and thorough recharging takes place, batteries in PV systems are installed into a shallow cycle (occasional deep cycle) application without the plate formation benefits of initial deep-cycling. Preparation of a battery for PV systems should include an initial charge that is simple and within the capabilities of the average consumer.

A procedure for initialization is necessary because of the remote nature of PV systems. The batteries may experience a significant interval between delivery and installation resulting in significant self-discharge. This problem can be resolved by establishing a universal procedure to initialize the battery before PV installation. If manufacturer's data is not available, presently accepted default parameters for charging (initializing) the battery prior to installation in a PV system will be developed here.

Initial Capacity and System Operating Capacity

As most batteries used in PV systems are originally designed for operation in other applications, (i.e., motive, standby, etc.) the battery's capacity is rated for use in that application. Each application has a different method for preparation and use of the battery. The capacity initially available from a battery (when properly charged) may vary between 80-100% of the normal rated capacity, depending on battery type and manufacturer process [7,11,12].

Initial Capacity is the term used here for the capacity derived from a battery after a single charge is applied to the battery upon receipt. Initial capacity will give a value indicative of available capacity without structured deep-cycling (formation). Normally a battery will increase in capacity as it is cycled. However, laboratory data at Sandia and the Florida Solar Energy Center has shown that capacity will not increase above the initial capacity under typical PV system design parameters [8-12]. Much of this is due to the limited time for recharge, low charge rates, the use of a charge controller and the controller's set-points.

Operating Capacity is the actual available capacity given the PV system operating parameters. This value may vary from the initial capacity depending on the Charge controller's voltage regulation (Vr) set-points and the system design. Vr set-points are often set at conservative values to reduce water loss and therefore extend maintenance intervals at the expense of available capacity and cycle life. In the case of low Vr set-points, excessive sulfation and electrolyte stratification typically occur and have been shown to reduce cycle life [11].

Figure 5 shows the initial capacity test at C/20 and the operating capacity at the Vr test rate (C/33) for a typical test just prior to the Vr test. In this case the capacities are fairly close, in other situations the difference may be greater. It is also noticeable that the capacity test at the end of the Vr test shows the battery capacity being sustained.

Charge Acceptance

Charge acceptance during recharge (from daily discharge) and subsequent charge regulation period will vary depending on the health of the battery, state-of-charge, degree of sulfation, temperature, and charge rate. How much this charge acceptance changes with these variables is not clearly documented and is critical to determining how much overcharge the system may be capable of delivering. Many PV systems are designed using robust thick plate deep-cycle batteries because of the increased cycle life quoted by the manufacturer.

These test procedures will help in defining how battery design affects charge acceptance, battery capacity, and cycle life when PV system operating parameters are varied.

Percent of Overcharge

Most battery manufacturers have data available as to what percentage of overcharge is required to return their battery to a "full state-of-charge" from the previous discharge. Tests at the Florida Solar Energy Center [15] have shown the percentage of overcharge required to return to a full state-of-charge varies according to depth-of-discharge and charge rate. PV systems have only a short period each day to fully recharge the battery and by adjusting the charge controller set-points the quantity of overcharge can be controlled. Overcharge is dependent on the PV array to load ratio and regulation voltage. As the overcharge is increased so does water consumption. In the end, the need for overcharge has to be balanced with the need to minimize water consumption.

Figure 6 shows a set of overcharge data with various Vr set-points with a C/33 charge rate, 10% depth-of-discharge and constant voltage regulation on an absorbed glass matte VRLA battery. On the right side of the graph is a list of the Ah capacities measured at the end of each of the 20 cycles. These capacity tests were performed to 11.4 volts. The 65 Ah at 11.4 volts is equivalent to 80Ah to 10.5 volts as shown by the initial capacity test that was performed prior to the Vr tests. The 14.1 volt number is highlighted because it shows a lower level of overcharge while maintaining the highest capacity.

The objective is to find a Vr setpoint that provides a stable and acceptable overcharge. With overcharge shown as increasing, we have reached a point of diminishing returns (14.2-14.4v). No additional capacity is available but we know we are exceeding the electrolysis threshold and more water will be lost than at the lower Vr set-points. As batteries have known inefficiencies, a decreasing percentage shows we will eventually be entering into a deficit situation (13.8-14.0v). This data provides us with reasonable knowledge that the 14.1 volts will minimize undercharging while limiting overcharging.

Voltage Regulation (Vr)

Because the charge controller is necessary to reduce overcharge during peak solar resource periods, it can be the most decisive component in determining how much recharge is provided to the battery. Most charge controllers are voltage controlled and at the mercy of reading the battery voltage for state-of-charge information. When regulation begins (at Vr set point), the controller will begin to limit current or disconnect the PV entirely until a specific battery voltage (voltage regulation reconnect-Vrr) is reached. [13]. Vrr is the battery voltage at which charging is resumed. Subtracting Vrr from Vr will provide the voltage regulation hysterisis (Vrh). Vrh can be anywhere from 0-volts (constant potential) to 3-volts (on/off-type control). Vrh is typically 0.8-1.0 volts for flooded lead-antimony batteries.

Voltage regulation parameters (Vr & Vrh) must be determined prior to beginning the cycle life test as results will vary with different values. Therefore it is necessary to select a Vr based on previous experience with PV systems or perform the Vr setpoint test.

Cycle Life

Cycle life is one of the most important characteristics when selecting a battery for a PV system. The cycle life data presently available has proven to be reasonable in PV systems when the batteries are fully recharged [8]. However, battery manufacturer's cycle life data are derived from conditions that result in excessive watering of the batteries. If charging is reduced to levels at which water loss is minimized for PV systems, then battery cycle life becomes questionable.

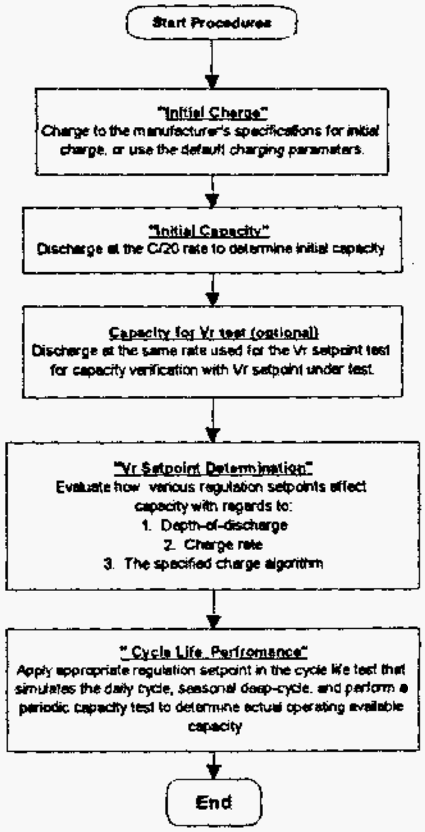
Charging batteries to a "less than full" state may actually extend or reduce battery cycle life. Testing at Sandia has shown that there is an optimum middle ground between over and undercharging in which cycle life and maintenance intervals can be extended at the cost of available battery capacity.

Cycle life will be determined based on the specific system design parameters chosen for the test. Cycle life is presently defined in this effort as the inability of the battery to deliver 50% of the initial capacity during periods when full recharge is available (using initial capacity tests as reference).

Proposed Test Procedures

Sandia is part of an effort to establish a set of repeatable documented procedures that will allow an economical simulation of PV operating conditions. These procedures will put the battery into conditions similar to those experienced in actual PV systems. These tests are being developed through a group effort comprised of battery manufacturers, PV system designers, Florida Solar Energy Center, and Sandia. At this point the procedures appear fairly solid, yielding the type of information desired. Figure 2 shows a flow chart of all of the procedures in the series presently in use.

Figure 2, Flowchart of Test Procedures



This information is presented as a working document to expose the nuances of the PV application. These test procedures will yield definitive information on the characteristics of batteries in PV systems and they are still under development.

Test equipment required

The intention is to make these procedures simple enough to be performed with basic power supply and relay control components or sophisticated battery test equipment. When a system designer is forced to use an unknown battery in place of a tested battery, these procedures can then be performed in a modest lab. If the unknown battery is inferior, then appropriate steps can be taken.

Figure 3 shows three basic configurations for equipment. Method One uses a sophisticated battery tester that allows programming of charge/discharge profiles, etc. Method Two uses the same equipment but inserts an actual charge controller between the battery and charge/discharge source. This allows the investigator to match a charge controller to the battery based on the design parameters used. Method Three shows basic power supply and relay control.

Initialization of Battery

The battery under test will be prepared under the guidelines in Table 1. This will be a single charge, which duplicates how the batteries may be put into service in actual PV systems. The investigator is encouraged to check battery manufacturer's literature for proper initial charge recommendations. There may be times when battery manufacturer's data on initial charging may not be available. This simple procedure for initialization may be performed in the field and will ensure adequate preparation of the battery.

Capacity Tests

Initial capacity will be determined by performing the procedures shown in Figure 7. This capacity test is at the manufacture's 20-hour rate to 1.75 volts per cell. If other discharge rates are used (i.e., Vr test) the manufacturer should be consulted for the appropriate cutoff voltage. If the manufacturer's cutoff voltage data is unavailable 1.75 volts per cell will be used

Another capacity test will be performed prior to the Vr set-points tests, at the rate identical to the discharge rate used in the Vr setpoint tests. This is to allow comparison of the actual operating capacity after 20 cycles because various charge/discharge rates and charge controller operation may vary performance dramatically. This battery voltage Vs Ah curve (Figure 5) will also be useful in determining available capacity during the cycle life test.

Figure 3, Possible test configurations

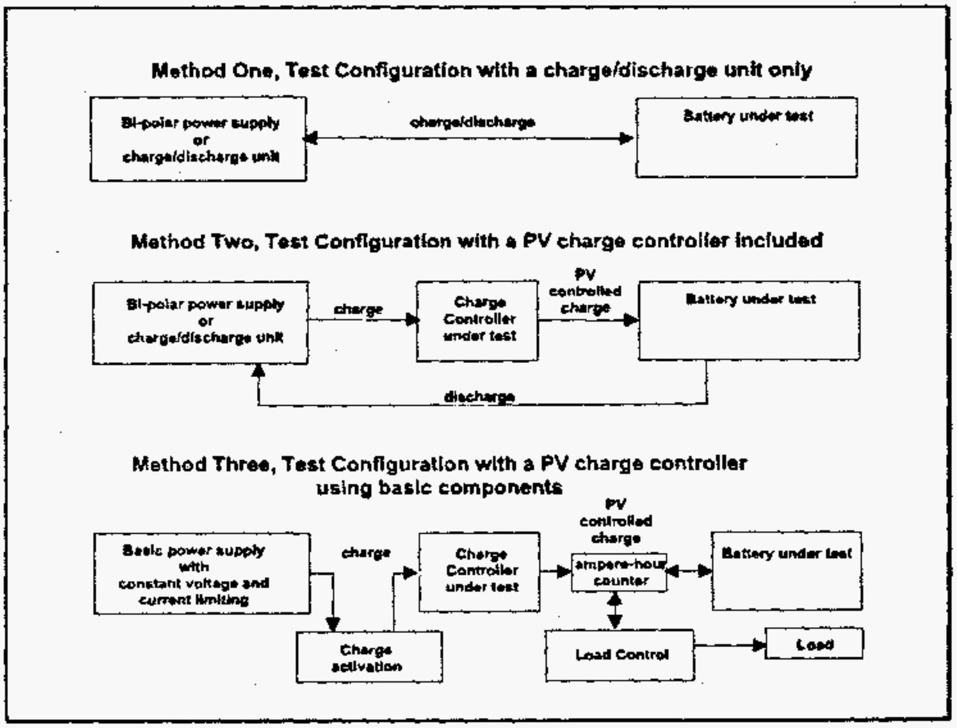


Table 1, Default Initial Charging Parameters

Type	Voltage limit, Vpc	Voltage limit, nominal 6/12v	Duration of constant voltage regulation or charge period
wet, lead-antimony	2.55	7.65/15.3	3 hours
wet, lead-calcium	2.66	7.98/16.0	3 hours
wet, lead-antimony/calcium	2.58	7.74/15.5	3 hours
VRLA, AGM calcium	2.37	7.11/14.2	10 hours
VRLA, AGM antimony/calcium	2.35	7.05/14.1	10 hours
VRLA, Gel, calcium	2.40	7.20/14.4	10 hours

NOTES: Current should be limited to 3.0 amperes per 100 Ah of manufacturer's 20-hr, rated capacity. VRLA=valve regulated lead-acid Vpc= volts per cell, AGM= Absorbed Glass Matte, Gel= gel electrolyte

Operating Parameter Determination and Cycle Profile (proposed)

Putting the battery into a cyclic profile similar to a PV application is the main point of this entire effort. Determining the test parameters to use is critical. The daily solar cycle is set at 4 hours for discharging, a 1/2 hour rest, 5 hours of charging, and a 1/2 hour rest. This simulates a reasonable approximation of the average solar day in peak charging hours (the value used by system designers) and allows two-plus cycles per day.

Charge Ah-to-load Ah ratio (C:L) is the potential charging ampere hours available (Ah) with respect to the load Ah. In a PV system this would be referred to as the PV array:load ratio. Variance in the C:L ratio will have a significant effect how well the battery is charged but needs to be maintained within realistic economic restraints of traditional PV system design parameters. The operational parameters for the test are based on using the battery capacity and DOD while calculating everything else from those values. This allows flexibility to adjust to the investigator's needs. Table 2 is provided as a default set of parameters that are advised if you have no other specific requirements. A charge rate greater than C/15 will not generally be found in stand-alone PV systems. Unless there is a specific need to investigate charging at rates greater than this, it is not advised to exceed C/15. Changing the charge current or load will affect the C:L Ratio.

For example, when testing a 100-Ah battery for 20% depth-of-discharge (DOD), the load, or daily depth of discharge (DDOD), equals 20 Ah. If the C:L = 1.20:1 (= 20% overcharge available), then the charge Ah = 24 Ah. Since the charge period = 5 hours, then charge current will be 24/5 = 4.8 amperes.

Table 2, Default Charge Rate & DOD Test Parameters (proposed recommendation)

DOD	Charge:Load Ratio	
10%	1.25:1	1.50:1
20%	1.25:1	1.50:1

Determine

1. Battery size in Ah using manufacturer's nominal 20-hr rate.
2. C:L Ratio. This is how much overcharge that will be available with respect to the discharge.
3. Daily depth of discharge in Ah.
4. Calculate discharge current by dividing the DOD by 4 (discharge period is 4 hours).
5. Calculate the Ah returned (Ahr), or Ah available for recharge, by multiplying the DOD in Ah by the C:L ratio.
6. Calculate the recharge current by dividing the Ahr by 5 (recharge period is 5 hours).

Example 1, 105 Ah battery, 10% DOD, 1.25:1 C:L ratio

1. Battery rated at 105 Ah for 20 hr rate.
2. Using a 1.25:1 C:L ratio, we will need 25% Ah in excess of the load Ah available for recharge.
3. For this example use 10% DOD.
4. 10% of 105Ah = 10.5 Ah load, 10.5 Ah divided by 4 = 2.6 ampere discharge rate.
5. 10.5 Ah multiplied by 125%=13.2 Ahr.
6. 13.2 Ahr/5 = 2.64 amperes for charging current.

Table 3, Default initial Vr set-points

	on/off controller		*constant voltage controller*	
Battery type	Voltage limit, vpc	Voltage limit, nominal 6/12v	Voltage limit, vpc	Voltage limit, nominal 6/12v
wet, lead-antimony	2.40	7.40/14.80	2.40	7.20/14.40
wet, lead-calcium	2.45	7.50/15.00	2.45	7.35/14.70
wet, lead-antimony/calcium	2.466	7.40/14.80	2.416	7.25/14.50
VRLA, AGM calcium	2.37	7.10/14.20	2.37	7.10/14.20
VRLA, AGM antimony/calcium	2.35	7.05/14.10	2.35	7.05/14.10
VRLA, Gel, calcium	2.40	7.20/14.40	2.40	7.20/14.40

Example 2, 105 Ah battery, 20% DOD, 1.5:1-C:L ratio:

1. Battery rated at 105 Ah for 20 hr rate.
2. Using a 1.50:1 C:L ratio, we will need 50% Ah in excess of the load Ah available for recharge.
3. For this example use 20% depth-of-discharge.
4. 20% of 105Ah = 21 Ah load, 21 Ah divided by 4 = 5.2 ampere discharge rate.
5. 21Ah multiplied by 150%=31.5 Ahr.
6. 31.5 Ahr/5 = 6.3 amperes for charging current.

Voltage Regulation Setpoint Determination

The Vr setpoint needs to be determined prior to initiating the cycle life test. Figure 8 shows the process by flowchart. By performing this test prior to the cycle life test, the investigator increases the chances of achieving a long cycle life on the first effort. This procedure requires the investigator to establish what parameters and charge controller algorithm they want to investigate. By entering into the solar day charge/discharge cycle for evaluation of the set-points, adjustments (Vr) can be made to deliver the appropriate level of overcharge required to maintain acceptable battery capacity and water loss parameters. The final decision for what the regulation setpoint should be in normal cycle use is based on: acceptable water loss/maintenance interval, available capacity, and percentage of overcharge delivered on each cycle.

Selection of the starting Vr setpoint can be taken from the manufacturer's suggestion's, PV system experience, or from Table 3, the Default initial Vr set-points. The values in Table 3 are close to the optimum Vr set-points given a C/25 charge rate and 20% DOD. When enough set-points have been examined to make a decision which meets your charging goals a choice can be made as to which setpoint is appropriate for the intended operation. The capacity data at the end of each setpoint test may not be absolute but will be relative to the other set-points tested.

Basis for deciding on appropriate Vr setpoint

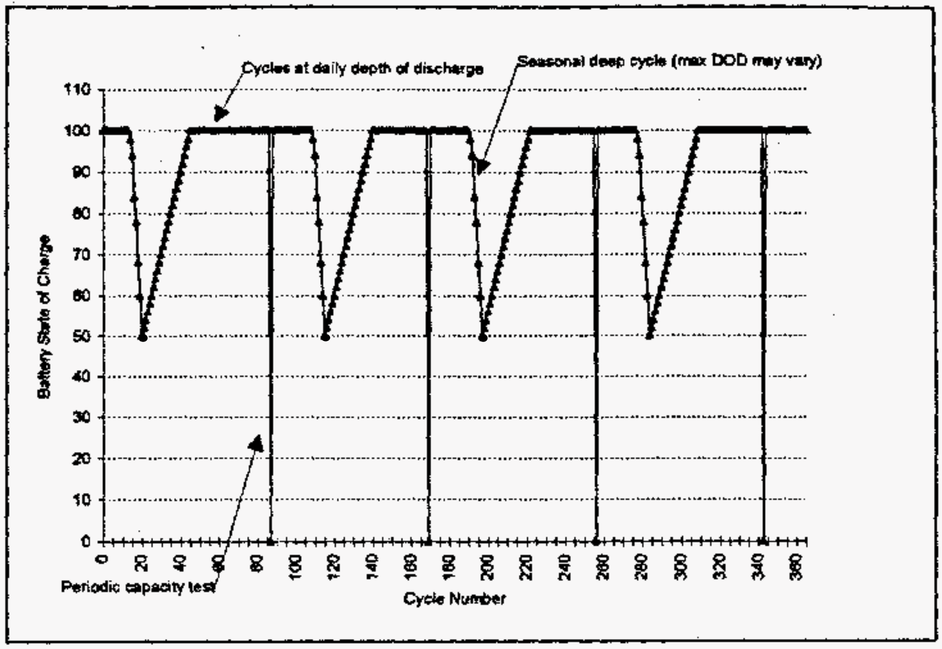
- *Percent of overcharge each cycle*
- *Predicted water loss/maintenance interval*
- *Available capacity measured*

To predict maintenance, the amount of overcharging needs to be tempered with the need for gassing, maintenance of available capacity, and what that operating state-of-charge will do to cycle life and maintenance intervals.

Cycle Life Determination

Determining an appropriate cycle life test profile is difficult, as PV systems will experience a variety of conditions. The profile here is an effort to establish a relatively easy profile while still maintaining the characteristics experienced in PV systems. Figure 9 shows the test process as it is presently defined (subject to change). This test will be used to determine battery cycle life as well as the ability of the Vr set-point's capability to perform as expected. New batteries are required for this test. Batteries put through the previous procedures are not recommended to be used as the amount of cycling and abuse given them may affect the results. The procedure for determining cycle life in the PV application is determined with a 360 cycle profile that is infinitely repeatable.

Figure 4, Cycle life test profile



This test will cycle the batteries in a scenario that resembles the daily charge/discharge cycles of a PV system and determine the cycle life characteristics of the battery. The basic test (Fig. 4) will include short periods of deficit charging (Ah discharged >Ahr) at specific intervals, allowing the system to recover with the available resources. This will imitate seasonal variations in solar resource. This is indicative of how a PV system will experience a week of poor weather and then be allowed to recover from its own charging source. A capacity test is introduced periodically in each cyclic period between deep cycles to determine actual operating capacity available in the battery. End of life will be characterized by the inability to deliver 50% of the operating capacity rating during normal cycling. The same cutoff voltage for initial capacity test will be used for the intermediate capacity test.

If the investigator desires to establish cycle life predictions at other depth-of-discharges, charge rates, charging set-points, charge algorithms, or temperatures, the test parameters may be modified to examine the effects of these variations. Temperature is not varied in these tests, and all tests are to be performed at a nominal 25°C +\-3°C ambient temperature. Stabilized temperature baths are suggested but not required.

Summary

The PV application exerts demands on the battery that are unique. The test procedures as they are presently defined have been successful in developing capacity and voltage regulation parameters for several batteries. These are newly developed batteries and others are older batteries, new to the PV application.

These test procedures are an effort to provide a simple approximation that closely resembles the demands of a PV system. Having these procedures defined and repeatable will allow more fair competition for battery products in the U.S. and in foreign countries. Many times PV systems designers are forced to use foreign made or batteries of unknown quality in PV systems, as there is no documented way to compare the rating used in specifying the batteries. These test procedures should help in resolving that problem and provide the PV system designer, as well as the PV system customer, a more reliable and effective photovoltaic system.

At present, these test procedures are being developed with the cooperation from various areas of interest in the PV application. Input from multiple areas is intended to ensure that the test procedures produced will be acceptable to all parties involved so they will be simple to perform and useful to the PV industry. These procedures will provide PV system designers and consumers the information needed to make battery selection based on comparing specifications that are well documented and relevant to the application.

Test development is proceeding at Sandia National Laboratories and the Florida Solar Energy Center and it is expected that the procedures will be published in an internationally recognized forum when completed.

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Robert Spotts, Photocomm, Inc.
Lane Garrett, ETA Engineering
Bob Hammond, Arizona State University

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Figure 5, Capacity and Vr setpoint tests

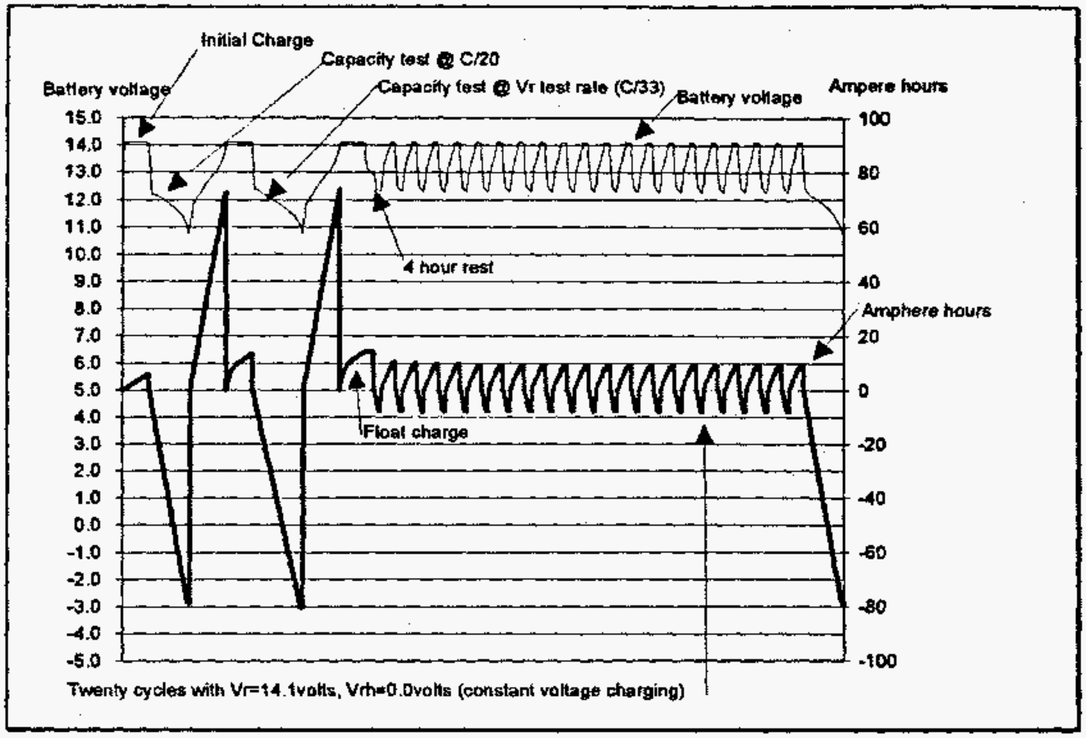

Figure 6, Percentage of overcharge for various Vr set-points

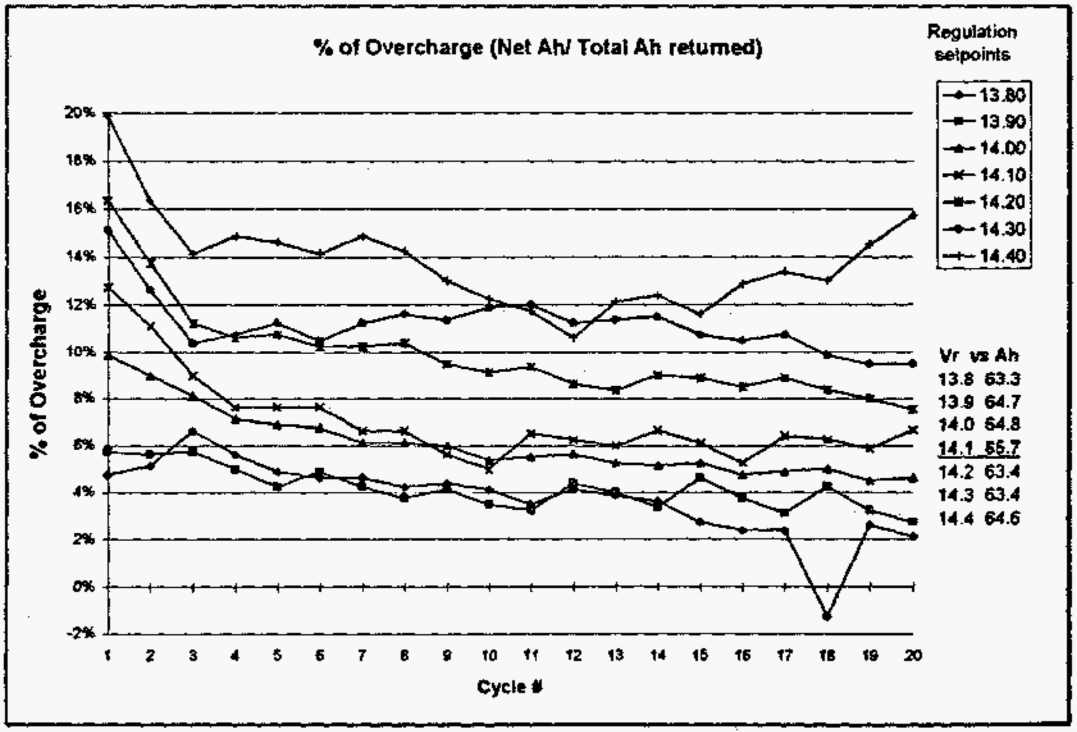

Figure 7, Initial Capacity Flowchart

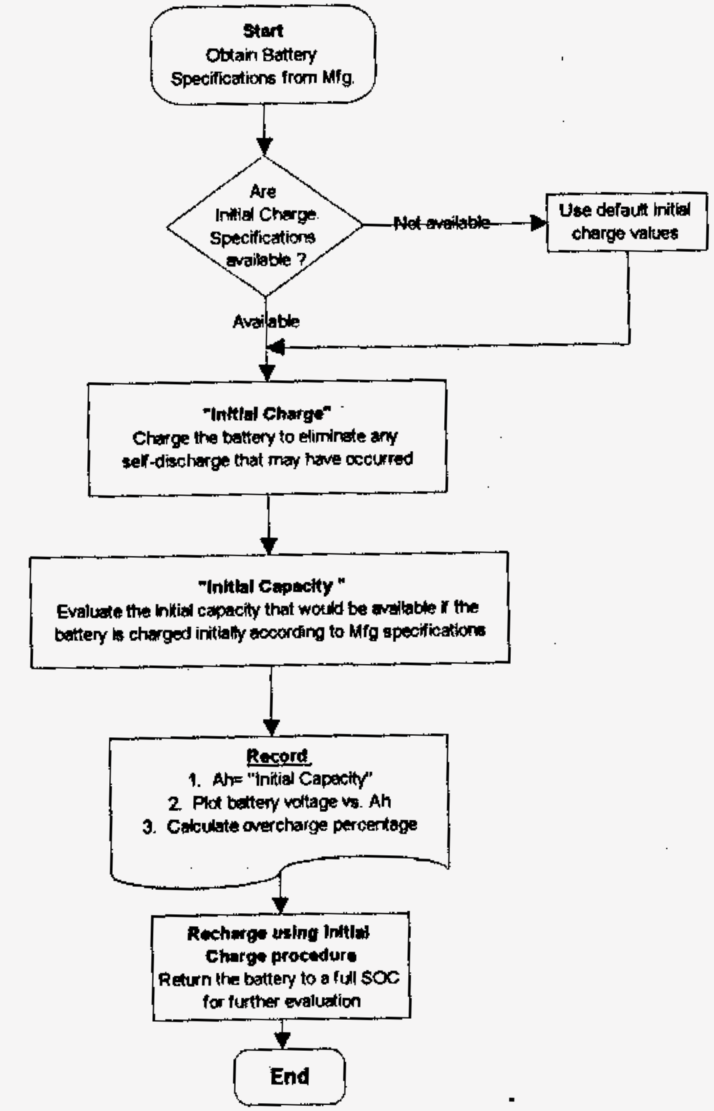

Figure 8, Voltage Regulation Setpoint Evaluation Flowchart

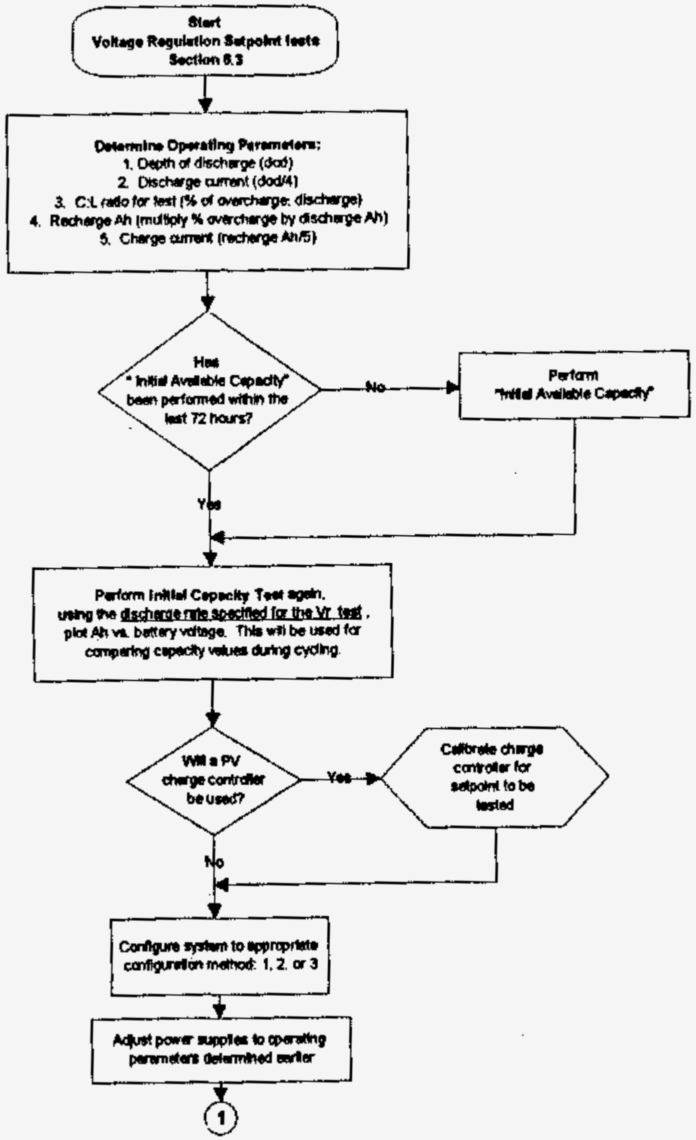

Figure 8 cont., Voltage Regulation Evaluation Flowchart

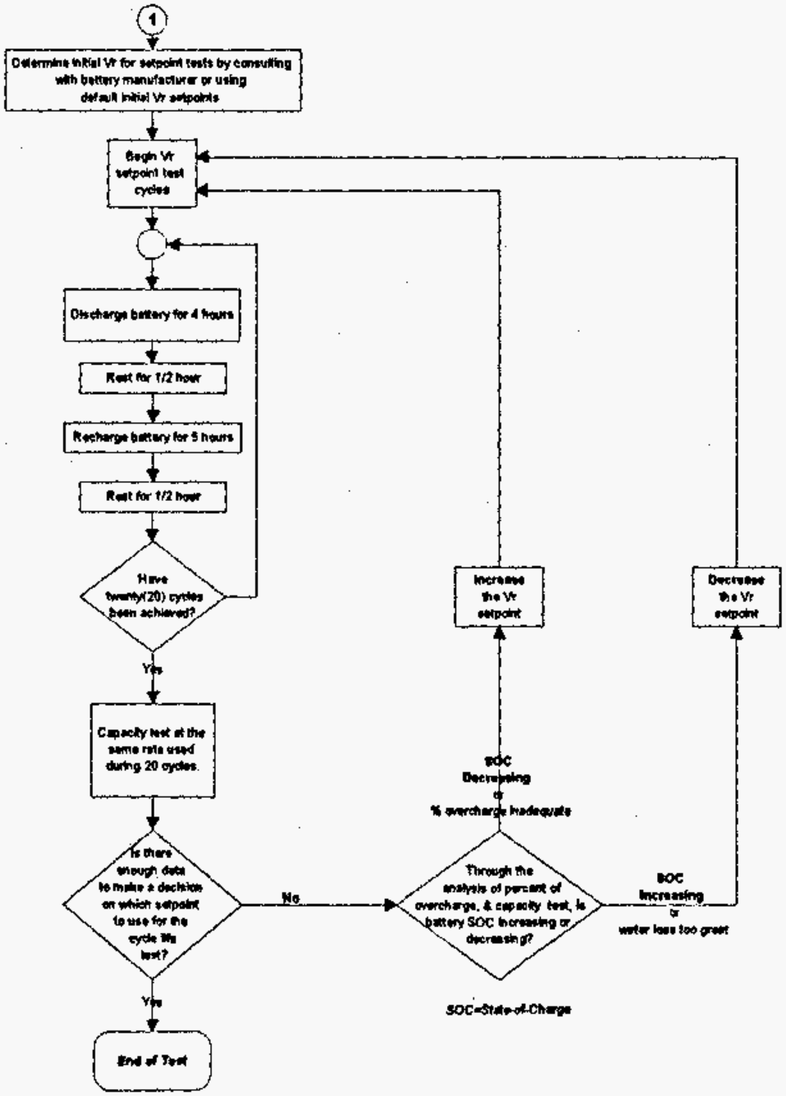

Figure 9, Cycle Life Test Flowchart