Batteries and Charge Control in Stand-Alone Photovoltaic Systems

Fundamentals and Application

January 15, 1997

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EXECUTIVE SUMMARY

This report presents an overview of battery technology and charge control strategies commonly used in stand-alone photovoltaic (PV) systems. This work is a compilation of information from several sources, including PV system design manuals, research reports, data from component manufacturers, and lessons learned from hardware evaluations.

Details are provided about the common types of flooded lead-acid, valve regulated lead-acid, and nickel-cadmium cells used in PV systems, including their design and construction, electrochemistry and operational performance characteristics. Comparisons are given for various battery technologies, and considerations for battery subsystem design, auxiliary systems, maintenance and safety are discussed.

Requirements for battery charge control in stand-alone PV systems are covered, including details about the various switching designs, algorithms, and operational characteristics. Daily operational profiles are presented for different types of battery charge controllers, providing an in-depth look at how these controllers regulate and limit battery overcharge in PV systems.

Most importantly, considerations are presented for properly selecting batteries and matching of the charge controller characteristics. Specific recommendations on voltage regulation set point for different charge control algorithms and battery types are listed to aid system designers.

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INTRODUCTION

This report presents fundamentals of battery technology and charge control strategies commonly used in stand-alone photovoltaic (PV) systems. This work is a compilation of information from several sources, including PV system design manuals, research reports and data from component manufacturers.

Details are provided about the common types of flooded lead-acid, valve regulated lead-acid, and nickel-cadmium cells used in PV systems, including their design and construction, electrochemistry and operational performance characteristics. Comparisons are given for various battery technologies, and considerations for battery subsystem design, auxiliary systems, maintenance and safety are discussed.

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Most importantly, considerations for properly selecting batteries and matching of the charge controller characteristics are presented. Specific recommendations on voltage regulation set point for different charge control algorithms and battery types are listed to aid system designers.

Purpose

This work was done to address a significant need within the PV industry regarding the application of batteries and charge control in stand-alone systems. Some of the more critical issues are listed in the following.

- Premature failure and lifetime prediction of batteries are major concerns within the PV industry.

- Batteries experience a wide range of operational conditions in PV applications, including varying rates of charge and discharge, frequency and depth of discharges, temperature fluctuations, and the methods and limits of charge regulation. These variables make it very difficult to accurately predict battery performance and lifetime in PV systems.

- Battery performance in PV systems can be attributed to both battery design and PV system operational factors. A battery which is not designed and constructed for the operational conditions experienced in a PV system will almost certainly fail prematurely. Just the same, abusive operational conditions and lack of proper maintenance will result in failure of even the more durable and robust deep-cycle batteries.

- Battery manufacturers' specifications often do not provide sufficient information for PV applications. The performance data presented by battery manufacturers is typically based on tests conducted at specified, constant conditions and is often not representative of battery operation in actual PV systems.

- Wide variations exist in charge controller designs and operational characteristics. Currently no standards, guidelines, or sizing practices exist for battery and charge controller interfacing.

Scope and Objectives

Following are some of the more important questions and issues addressed in this report.

- What are the basic battery types and classifications?
- What are the primary differences in the design and operational characteristics of different battery types?
- What are the principal mechanisms affecting battery failure and what are the common failure modes?
- What operation and maintenance procedures are needed to maintain battery performance and extend lifetime?
- Should pre-charging of batteries be done prior to their installation in PV systems?
- What are the consequences of undercharging and overcharging for various battery types?
- How should a battery subsystem be electrically designed in a PV system for optimal performance and safety?
- What are the different types and classification of battery charge controllers?
- What is the common terminology associated with battery charge controllers for PV systems?
- How do different types of charge controllers actually operate in PV systems?
- How do the rates of charge, charge regulation algorithm and set points affect battery performance and lifetime in PV systems?
- Is any particular control algorithm superior to other charge control algorithms? Under what conditions?
- Is equalization important for batteries in PV systems? What types and under what conditions?
- What are suggested design, selection and matching guidelines for battery application and charge control requirements in PV systems?

BATTERY TECHNOLOGY OVERVIEW

To properly select batteries for use in stand-alone PV systems, it is important that system designers have a good understanding of their design features, performance characteristics and operational requirements. The information in the following sections is intended as a review of basic battery characteristics and terminology as is commonly used in the design and application of batteries in PV systems.

Batteries in PV Systems

In stand-alone photovoltaic systems, the electrical energy produced by the PV array can not always be used when it is produced. Because the demand for energy does not always coincide with its production, electrical storage batteries are commonly used in PV systems. The primary functions of a storage battery in a PV system are to:

1. ***Energy Storage Capacity and Autonomy:*** to store electrical energy when it is produced by the *PV array* and to supply energy to *electrical loads* as needed or on demand.
2. ***Voltage and Current Stabilization:*** to supply power to *electrical loads* at stable voltages and currents, by suppressing or 'smoothing out' *transients* that may occur in PV systems.
3. ***Supply Surge Currents:*** to supply surge or high peak operating currents to *electrical loads* or appliances.

Battery Design and Construction

Battery manufacturing is an intensive, heavy industrial process involving the use of hazardous and toxic materials. Batteries are generally mass produced, combining several sequential and parallel processes to construct a complete battery unit. After production, initial charge and discharge cycles are conducted on batteries before they are shipped to distributors and consumers.

Manufacturers have variations in the details of their battery construction, but some common construction features can be described for most all batteries. Some important components of battery construction are described below.

Cell: The cell is the basic electrochemical unit in a battery, consisting of a set of *positive* and *negative plates* divided by *separators,* immersed in an *electrolyte* solution and enclosed in a *case*. In a typical *lead-acid* battery, each cell has a *nominal voltage* of about 2.1 volts, so there are 6 series cells in a nominal 12 volt battery. Figure 1 shows a diagram of a basic lead-acid battery cell.

Active Material: The active materials in a battery are the raw composition materials that form the *positive* and *negative* plates, and are reactants in the electrochemical *cell*. The amount of active material in a battery is proportional to the *capacity* a battery can deliver. In *lead-acid* batteries, the active materials are *lead dioxide* (PbO_2) in the positive plates and *metallic sponge lead* (Pb) in the negative plates, which react with a *sulfuric acid* (H_2SO_4) solution during battery operation.

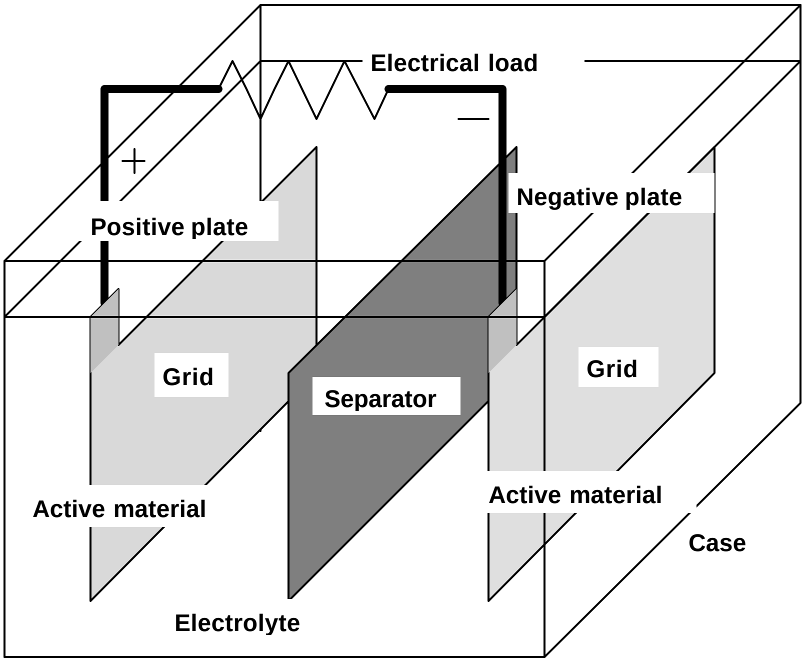


Figure 1. Battery cell composition

Electrolyte: The electrolyte is a conducting medium which allows the flow of current through ionic transfer, or the transfer of electrons between the *plates* in a battery. In a lead-acid battery, the electrolyte is a diluted *sulfuric acid* solution, either in liquid (flooded) form, gelled or absorbed in glass mats. In flooded nickel-cadmium cells, the electrolyte is an alkaline solution of potassium hydroxide and water. In most flooded battery types, periodic water additions are required to replenish the electrolyte lost through gassing. When adding water to batteries, it is very important to use distilled or de-mineralized water, as even the impurities in normal tap water can poison the battery and result in premature failure.

Grid: In a lead-acid battery, the grid is typically a lead alloy framework that supports the *active material* on a battery *plate*, and which also conducts current. Alloying elements such as *antimony* and *calcium* are often used to strengthen the lead grids, and have characteristic effects on battery performance such as *cycle* performance and *gassing*. Some grids are made by expanding a thin lead alloy sheet into a flat plate web, while others are made of long spines of lead with the active material plated around them forming tubes, or what are referred to as *tubular plates*.

Plate: A plate is a basic battery component, consisting of a *grid* and *active material,* sometimes called an *electrode*. There are generally a number of *positive* and *negative* plates in each battery *cell*, typically connected in *parallel* at a bus bar or inter-cell connector at the top of the plates. A pasted plate is manufactured by applying a mixture of *lead oxide*, *sulfuric acid*, fibers and water on to the *grid*. The thickness of the grid and plate affect the deep cycle performance of a battery. In automotive starting or SLI type batteries, many thin plates are used per cell. This results in maximum surface area for delivering high currents, but not much thickness and mechanical durability for deep and prolonged discharges. Thick plates are used for deep cycling applications such as for forklifts, golf carts and other electric vehicles. The thick plates permit deep discharges over long periods, while maintaining good adhesion of the active material to the grid, resulting in longer life.

Separator: A separator is a porous, insulating divider between the *positive* and *negative plates* in a battery, used to keep the plates from coming into electrical contact and short-circuiting, and which also allows the flow of *electrolyte* and ions between the positive and negative plates. Separators are made from micro-porous rubber, plastic or glass-wool mats. In some cases, the separators may be like an envelope, enclosing the entire plate and preventing shed materials from creating short circuits at the bottom of the plates.

Element: In element is defined as a stack of positive and negative plate groups and separators, assembled together with plate straps interconnecting the positive and negative plates.

Terminal Posts: Terminal posts are the external positive and negative electrical connections to a battery. A battery is connected in a PV system and to electrical loads at the terminal posts. In a lead-acid battery the posts are generally lead or a lead alloy, or possibly stainless steel or copper-plated steel for greater corrosion resistance. Battery terminals may require periodic cleaning, particularly for flooded designs. It is also recommended that the clamps or connections to battery terminals be secured occasionally as they may loosen over time.

Cell Vents: During battery charging, gasses are produced within a battery that may be vented to the atmosphere. In flooded designs, the loss of electrolyte through gas escape from the cell vents it a normal occurrence, and requires the periodic addition of water to maintain proper electrolyte levels. In sealed, or valve-regulated batteries, the vents are designed with a pressure relief mechanism, remaining closed under normal conditions, but opening during higher than normal battery pressures, often the result of overcharging or high temperature operation. Each cell of a complete battery unit has some type of cell vent.

Flame arrestor vent caps are commonly supplied component on larger, industrial battery systems. The venting occurs through a charcoal filter, designed to contain a cell explosion to one cell, minimizing the potential for a catastrophic explosion of the entire battery bank.

Case: Commonly made from a hard rubber or plastic, the case contains the *plates*, *separators* and *electrolyte* in a battery. The case is typically enclosed, with the exception of inter-cell connectors which attach the plate assembly from one cell to the next, terminal posts, and *vents* or caps which allow *gassing* products to escape and to permit water additions if required. Clear battery cases or containers allow for easy monitoring of electrolyte levels and battery plate condition. For very large or tall batteries, plastic cases are often supported with an external metal or rigid plastic casing.

Battery Types and Classifications

Many types and classifications of batteries are manufactured today, each with specific design and performance characteristics suited for particular applications. Each battery type or design has its individual strengths and weaknesses. In PV systems, *lead-acid* batteries are most common due to their wide availability in many sizes, low cost and well understood performance characteristics. In a few critical, low temperature applications *nickel-cadmium* cells are used, but their high initial cost limits their use in most PV systems. There is no "perfect battery" and it is the task of the PV system designer to decide which battery type is most appropriate for each application.

In general, electrical storage batteries can be divided into to major categories, *primary* and *secondary* batteries.

Primary Batteries

Primary batteries can store and deliver electrical energy, but *can not be recharged*. Typical carbon-zinc and lithium batteries commonly used in consumer electronic devices are primary batteries. Primary batteries are not used in PV systems because they can not be recharged.

Secondary Batteries

A secondary battery can store and deliver electrical energy, and *can also be recharged* by passing a current through it in an opposite direction to the discharge current. Common *lead-acid* batteries used in automobiles and PV systems are secondary batteries. Table 1 lists common secondary battery types and their characteristics which are of importance to PV system designers. A detailed discussion of each battery type follows.

Table 1. Secondary Battery Types and Characteristics

Battery Type	Cost	Deep Cycle Performance	Maintenance
Flooded Lead-Acid			
Lead-Antimony	low	good	high
Lead-Calcium Open Vent	low	poor	medium
Lead-Calcium Sealed Vent	low	poor	low
Lead Antimony/Calcium Hybrid	medium	good	medium
Captive Electrolyte Lead-Acid (VRLA)			
Gelled	medium	fair	low
Absorbed Glass Mat	medium	fair	low
Nickel-Cadmium			
Sintered-Plate	high	good	none
Pocket-Plate	high	good	medium

Lead-Acid Battery Classifications

Many types of lead-acid batteries are used in PV systems, each having specific design and performance characteristics. While there are many variations in the design and performance of lead-acid cells, they are often classified in terms of one of the following three categories.

SLI Batteries

Starting, lighting and ignition (SLI) batteries are a type of lead-acid battery designed primarily for *shallow cycle* service, most often used to power automobile starters. These batteries have a number of thin positive and negative plates per cell, designed to increase the total plate active surface area. The large number of plates per cell allows the battery to deliver high discharge currents for short periods. While they are not designed for long life under deep cycle service, SLI batteries are sometimes used for PV systems in developing countries where they are the only type of battery locally manufactured. Although not recommended for most PV applications, SLI batteries may provide up to two years of useful service in small stand-alone PV systems where the *average daily depth of discharge* is limited to 10-20%, and the maximum *allowable depth of discharge* is limited to 40-60%.

Motive Power or Traction Batteries

Motive power or traction batteries are a type of lead acid battery designed for deep discharge cycle service, typically used in electrically operated vehicles and equipment such as golf carts, fork lifts and floor sweepers. These batteries have a fewer number of plates per cell than SLI batteries, however the plates are much thicker and constructed more durably. High content *lead-antimony grids* are primarily used in motive power batteries to enhance deep cycle performance. Traction or motive power batteries are very popular for use in PV systems due to their deep cycle capability, long life and durability of design.

Stationary Batteries

Stationary batteries are commonly used in un-interruptible power supplies (UPS) to provide backup power to computers, telephone equipment and other critical loads or devices. Stationary batteries may have characteristics similar to both SLI and motive power batteries, but are generally designed for occasional deep discharge, limited cycle service. Low water loss *lead-calcium* battery designs are used for most stationary battery applications, as they are commonly float charged continuously.

Types of Lead-Acid Batteries

There are several types of lead-acid batteries manufactured. The following sections describe the types of lead-acid batteries commonly used in PV systems.

Lead-Antimony Batteries

Lead-antimony batteries are a type of lead-acid battery which use antimony (Sb) as the primary alloying element with lead in the plate grids. The use of lead-antimony alloys in the grids has both advantages and disadvantages. Advantages include providing greater *mechanical strength* than pure lead grids, and excellent *deep discharge* and *high discharge rate* performance. Lead-antimony grids also limit the shedding of active material and have better lifetime than lead-calcium batteries when operated at higher temperatures.

Disadvantages of lead-antimony batteries are a *high self-discharge rate*, and as the result of necessary overcharge, require frequent water additions depending on the temperature and amount of overcharge.

Most lead-antimony batteries are flooded, open vent types with removable caps to permit water additions. They are well suited to application in PV systems due to their deep cycle capability and ability to take abuse, however they do require periodic water additions. The frequency of water additions can be minimized by the use of *catalytic recombination caps* or battery designs with excess electrolyte reservoirs. The health of flooded, open vent lead-antimony batteries can be easily checked by measuring the *specific gravity* of the electrolyte with a *hydrometer*.

Lead-antimony batteries with thick plates and robust design are generally classified as motive power or traction type batteries, are widely available and are typically used in electrically operated vehicles where deep cycle long-life performance is required.

Lead-Calcium Batteries

Lead-calcium batteries are a type of lead-acid battery which use calcium (Ca) as the primary alloying element with lead in the plate grids. Like lead-antimony, the use of lead-calcium alloys in the grids has both advantages and disadvantages. Advantages include providing greater *mechanical strength* than pure lead grids, a *low self-discharge rate*, and *reduced gassing* resulting in lower water loss and lower maintenance requirements than for lead-antimony batteries. Disadvantages of lead-calcium batteries include *poor charge acceptance* after deep discharges and shortened battery life at higher operating temperatures and if discharged to greater than 25% *depth of discharge* repeatedly.

Flooded Lead-Calcium, Open Vent

Often classified as stationary batteries, these batteries are typically supplied as individual 2 volt cells in capacity ranges up to and over 1000 ampere-hours. Flooded lead-calcium batteries have the advantages of low self discharge and low water loss, and may last as long as 20 years in stand-by or float service. In PV applications, these batteries usually experience short lifetimes due to sulfation and stratification of the electrolyte unless they are charged properly.

Flooded Lead-Calcium, Sealed Vent

Primarily developed as 'maintenance free' automotive starting batteries, the capacity for these batteries is typically in the range of 50 to 120 ampere-hours, in a nominal 12 volt unit. Like all lead-calcium designs, they are intolerant of overcharging, high operating temperatures and deep discharge cycles. They are “maintenance free” in the sense that you do not add water, but they are also limited by the fact that you can not add water which generally limits their useful life. This battery design incorporates sufficient reserve electrolyte to operate over its typical service life without water additions. These batteries are often employed in small stand-alone PV systems such as in rural homes and lighting systems, but must be carefully charged to achieve maximum performance and life. While they are low cost, they are really designed for shallow cycling, and will generally have a short life in most PV applications

An example of this type of battery that is widely produced throughout the world is the Delco 2000. It is relatively low cost and suitable for unsophisticated users that might not properly maintain their battery water level. However, it is really a modified SLI battery, with many thin plates, and will only provide a couple years of useful service in most PV systems.

Lead-Antimony/Lead-Calcium Hybrid

These are typically flooded batteries, with capacity ratings of over 200 ampere-hours. A common design for this battery type uses *lead-calcium* tubular *positive* electrodes and pasted *lead-antimony negative* plates. This design combines the advantages of both lead-calcium and lead-antimony design, including good deep cycle performance, low water loss and long life. *Stratification* and *sulfation* can also be a problem with these batteries, and must be treated accordingly. These batteries are sometimes used in PV systems with larger capacity and deep cycle requirements. A common hybrid battery using tubular plates is the Exide Solar battery line manufactured in the United States.

Captive Electrolyte Lead-Acid Batteries

Captive electrolyte batteries are another type of lead-acid battery, and as the name implies, the electrolyte is *immobilized* in some manner and the battery is sealed under normal operating conditions. Under excessive overcharge, the normally sealed *vents* open under gas pressure. Often captive electrolyte batteries are referred to as *valve regulated lead acid* (VRLA) batteries, noting the pressure regulating mechanisms on the cell vents. *Electrolyte* can not be replenished in these battery designs, therefore they are intolerant of excessive overcharge.

Captive electrolyte lead-acid batteries are popular for PV applications because they are spill proof and easily transported, and they require no water additions making them ideal for remote applications were maintenance is infrequent or unavailable. However, a common failure mode for these batteries in PV systems is excessive overcharge and loss of electrolyte, which is accelerated in warm climates. For this reason, it is essential that the *battery charge controller* regulation set points are adjusted properly to prevent overcharging.

This battery technology is very sensitive to charging methods, regulation voltage and temperature extremes. Optimal charge regulation voltages for captive electrolyte batteries varies between designs, so it is necessary to follow manufacturers recommendations when available. When no information is available, the charge regulation voltage should be limited to no more than 14.2 volts at 25 ^{o}C for nominal 12 volt batteries. The recommended charging algorithm is *constant-voltage*, with *temperature compensation* of the regulation voltage required to prevent overcharge.

A benefit of captive or immobilized electrolyte designs is that they are less susceptible to freezing compared to flooded batteries. Typically, lead-calcium grids are used in captive electrolyte batteries to minimize gassing, however some designs use lead-antimony/calcium hybrid grids to gain some of the favorable advantages of lead-antimony batteries.

In the United States, about one half of the small remote PV systems being installed use captive electrolyte, or sealed batteries. The two most common captive electrolyte batteries are the *gelled* electrolyte and *absorbed glass mat* designs.

Gelled Batteries

Initially designed for electronic instruments and consumer devices, gelled lead-acid batteries typically use lead-calcium grids. The electrolyte is 'gelled' by the addition of silicon dioxide to the electrolyte, which is then added to the battery in a warm liquid form and gels as it cools. Gelled batteries use an internal recombinant process to limit gas escape from the battery, reducing water loss. Cracks and voids develop within the gelled electrolyte during the first few cycles, providing paths for gas transport between the positive and negative plates, facilitating the recombinant process.

Some gelled batteries have a small amount of *phosphoric acid* added to the electrolyte to improve the deep discharge cycle performance of the battery. The phosphoric acid is similar to the common commercial corrosion inhibitors and metal preservers, and minimizes grid oxidation at low states of charge.

Absorbed Glass Mat (AGM) Batteries

Another sealed, or valve regulated lead-acid battery, the electrolyte in an AGM battery is absorbed in glass mats which are sandwiched in layers between the plates. However, the electrolyte is not gelled. Similar in other respects to gelled batteries, AGM batteries are also intolerant to overcharge and high operating temperatures. Recommended charge regulation methods stated above for gelled batteries also apply to AGMs.

A key feature of AGM batteries is the phenomenon of internal gas recombination. As a charging lead-acid battery nears full state of charge, hydrogen and oxygen gasses are produced by the reactions at the negative and positive plates, respectively. In a flooded battery, these gasses escape from the battery through the vents, thus requiring periodic water additions. In an AGM battery the excellent ion transport properties of the liquid electrolyte held suspended in the glass mats, the oxygen molecules can migrate from the positive plate and recombine with the slowly evolving hydrogen at the negative plate and form water again. Under conditions of controlled charging, the pressure relief vents in AGM batteries are designed to remain closed, preventing the release of any gasses and water loss.

Lead-Acid Battery Chemistry

Now that the basic components of a battery have been described, the overall electrochemical operation of a battery can be discussed. Referring to Figure 10-1, the basic lead-acid battery cell consists of sets positive and negative plates, divided by separators, and immersed in a case with an electrolyte solution. In a fully charged lead-acid cell, the positive plates are lead dioxide (PbO_2), the negative plates are sponge lead (Pb), and the electrolyte is a diluted sulfuric acid solution. When a battery is connected to an electrical load, current flows from the battery as the active materials are converted to lead sulfate ($PbSO_4$).

Lead-Acid Cell Reaction

The following equations show the electrochemical reactions for the lead-acid cell. During battery discharge, the directions of the reactions listed goes from left to right. During battery charging, the direction of the reactions are reversed, and the reactions go from right to left. Note that the elements as well as charge are balanced on both sides of each equation.

At the positive plate or electrode:

$$PbO_2 + 4H^+ + 2e^- \Leftrightarrow Pb^{2+} + 2H_2O$$

$$Pb^{2+} + SO_4^{2-} \Leftrightarrow PbSO_4$$

At the negative plate or electrode:

$$Pb \Leftrightarrow Pb^{2+} + 2e^-$$

$$Pb^{2+} + SO_4^{2-} \Leftrightarrow PbSO_4$$

Overall lead-acid cell reaction:

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O$$

Some consequences of these reactions are interesting and important. As the battery is discharged, the active materials PbO_2 and Pb in the positive and negative plates, respectively, combine with the sulfuric acid solution to form $PbSO_4$ and water. Note that in a fully discharged battery the active materials in both the positive and negative plates are converted to $PbSO_4$, while the sulfuric acid solution is converted to water. This dilution of the electrolyte has important consequences in terms of the electrolyte *specific gravity* and freezing point that will be discussed later.

Formation

Forming is the process of initial battery *charging* during manufacture. Formation of a lead-acid battery changes the *lead oxide* (PbO) on the *positive plate grids* to *lead dioxide* (PbO_2), and to *metallic sponge lead* (Pb) on the *negative* plates. The extent to which a battery has been formed during manufacture dictates the need for additional cycles in the field to achieve *rated capacity*.

Specific Gravity

Specific gravity is defined as the ratio of the density of a solution to the density of water, typically measured with a *hydrometer*. By definition, water has a specific gravity of one. In a lead-acid battery, the electrolyte is a diluted solution of sulfuric acid and water. In a fully charged battery, the electrolyte is approximately 36% sulfuric acid by weight, or 25% by volume, with the remainder water. The specific gravity of the electrolyte is related to the battery *state of charge*, depending on the design *electrolyte* concentration and *temperature*.

In a fully charged flooded lead-acid battery, the specific gravity of the electrolyte is typically in the range of 1.250 to 1.280 at a temperature of 27 ^{o}C, meaning that the density of the electrolyte is between 1.25 and 1.28 times that of pure water. When the battery is discharged, the hydrogen (H^+) and sulfate (SO_4^{2-}) ions from the sulfuric acid solution combine with the active materials in the positive and negative plates to form lead sulfate ($PbSO_4$), decreasing the specific gravity of the electrolyte. As the battery is discharged to greater depths, the sulfuric acid solution becomes diluted until there are no ions left in solution. At this point the battery is fully discharged, and the electrolyte is essentially water with a specific gravity of one.

Concentrated sulfuric acid has a very low freezing point (less than -50 ^{o}C) while water has a much higher freezing point of 0 ^{o}C. This has important implications in that the freezing point of the electrolyte in a lead-acid battery varies with the concentration or specific gravity of the electrolyte. As the battery becomes discharged, the specific gravity decreases resulting in a higher freezing point for the electrolyte.

Lead-acid batteries used in PV systems may be susceptible to freezing in some applications, particularly during cold winters when the batteries may not be fully charged during below average insolation periods. The PV system designer must carefully consider the temperature extremes of the application along with the anticipated battery state of charge during the winter months to ensure that lead-acid batteries are not subjected to freezing. Table 2 shows the properties and freezing points for sulfuric acid solutions.

Table 2. Properties of Sulfuric Acid Solutions

Specific Gravity	H_2SO_4 (Wt%)	H_2SO_4 (Vol%)	Freezing Point (^{o}C)
1.000	0.0	0.0	0
1.050	7.3	4.2	-3.3
1.100	14.3	8.5	-7.8
1.150	20.9	13.0	-15
1.200	27.2	17.1	-27

1.250	33.4	22.6	-52
1.300	39.1	27.6	-71

Adjustments to Specific Gravity

In very cold or tropical climates, the specific gravity of the sulfuric acid solution in lead-acid batteries is often adjusted from the typical range of 1.250 to 1.280. In tropical climates where freezing temperatures do not occur, the electrolyte specific gravity may be reduced to between 1.210 and 1.230 in some battery designs. This lower concentration electrolyte will lessen the degradation of the separators and grids and prolong the battery's useful service life. However, the lower specific gravity decreases the storage capacity and high discharge rate performance of the battery. Generally, these factors are offset by the fact that the battery is generally operating at higher than normal temperatures in tropical climates.

In very cold climates, the specific gravity of the electrolyte may be increased above the typical range of 1.250 to 1.280 to values between 1.290 and 1.300. By increasing the electrolyte concentration, the electrochemical activity in the battery is accelerated, improving the low temperature capacity and lowers the potential for battery freezing. However, these higher specific gravities generally reduce the useful service life of a battery.

While the specific gravity can also be used to estimate the state of charge of a lead-acid battery, low or inconsistent specific gravity reading between series connected cells in a battery may indicate sulfation, stratification, or lack of equalization between cells. In some cases a cell with low specific gravity may indicate a cell failure or internal short-circuit within the battery. Measurement of specific gravity can be a valuable aid in the routine maintenance and diagnostics of battery problems in stand-alone PV systems.

Sulfation

Sulfation is a normal process that occurs in lead-acid batteries resulting from prolonged operation at partial states of charge. Even batteries which are frequently fully charged suffer from the effects of sulfation as the battery ages. The sulfation process involves the growth of lead sulfate crystals on the positive plate, decreasing the active area and capacity of the cell. During normal battery discharge, the active materials of the plates are converted to lead sulfate. The deeper the discharge, the greater the amount of active material that is converted to lead sulfate. During recharge, the lead sulfate is converted back into lead dioxide and sponge lead on the positive and negative plates, respectively. If the battery is recharged soon after being discharged, the lead sulfate converts easily back into the active materials.

However, if a lead-acid battery is left at less than full state of charge for prolonged periods (days or weeks), the lead sulfate crystallizes on the plate and inhibits the conversion back to the active materials during recharge. The crystals essentially "lock away" active material and prevent it from reforming into lead and lead dioxide, effectively reducing the capacity of the battery. If the lead sulfate crystals grow too large, they can cause physical damage to the plates. Sulfation also leads to higher internal resistance within the battery, making it more difficult to recharge.

Sulfation is a common problem experienced with lead-acid batteries in many PV applications. As the PV array is sized to meet the load under average conditions, the battery must sometimes be used to supply reserve energy during periods of excessive load usage or below average insolation. As a consequence, batteries in most PV systems normally operate for some length of time over the course of a year at partial states of charge, resulting in some degree of sulfation. The longer the period and greater the depth of discharge, the greater the extent of sulfation.

To minimize sulfation of lead acid batteries in photovoltaic systems, the PV array is generally designed to recharge the battery on the average daily conditions during the worst insolation month of the year. By sizing for the worst month's weather, the PV array has the best chance of minimizing the seasonal battery depth of discharge. In hybrid systems using a backup source such as a generator or wind turbine, the backup source can be effectively used to keep the batteries fully charged even if the PV array can not. In general, proper battery and array sizing, as well as periodic *equalization* charges can minimize the onset of sulfation.

Stratification

Stratification is a condition that can occur in flooded lead-acid batteries in which the concentration or specific gravity of the electrolyte increases from the bottom to top of a cell. Stratification is generally the result of undercharging, or not providing enough overcharge to gas and agitate the electrolyte during finish charging. Prolonged stratification can result in the bottom of the plates being consumed, while the upper portions remaining in relatively good shape, reducing battery life and capacity. Tall stationary cells, typically of large capacity, are particularly prone to stratification when charged at low rates. Periodic equalization charges thoroughly mix the electrolyte and can prevent stratification problems.

Nickel-Cadmium Batteries

Nickel-cadmium (Ni-Cad) batteries are *secondary*, or *rechargeable* batteries, and have several advantages over lead-acid batteries that make them attractive for use in stand-alone PV systems. These advantages include *long life*, *low maintenance*, survivability from excessive discharges, excellent low temperature *capacity retention*, and *non-critical voltage regulation* requirements. The main disadvantages of nickel-cadmium batteries are their *high cost* and limited availability compared to lead-acid designs.

A typical nickel-cadmium cell consists of positive electrodes made from *nickel-hydroxide* (NiO(OH))and negative electrodes made from *cadmium* (Cd) and immersed in an alkaline *potassium hydroxide* (KOH) electrolyte solution. When a nickel-cadmium cell is discharged, the nickel hydroxide changes form ($Ni(OH)_2$) and the cadmium becomes cadmium hydroxide ($Cd(OH)_2$). The concentration of the electrolyte does not change during the reaction so the freezing point stays very low.

Nickel-Cadmium Battery Chemistry

Following are the electrochemical reactions for the flooded nickel-cadmium cell:

At the positive plate or electrode:

$$2NiO(OH) + 2H_2O + 2e^- \Leftrightarrow 2Ni(OH)_2 + 2OH^-$$

At the negative plate or electrode:

$$Cd + 2OH^- \Leftrightarrow Cd(OH)_2 + 2e^-$$

Overall nickel cadmium cell reaction:

$$Cd + 2NiO(OH) + 2H_2O \Leftrightarrow Cd(OH)_2 + 2Ni(OH)_2$$

Notice these reactions are reversible and that the elements and charge are balanced on both sides of the equations. The discharge reactions occur from left to right, while the charge reactions are reversed.

The nominal voltage for a nickel-cadmium cell is 1.2 volts, compared to about 2.1 volts for a lead-acid cell, requiring 10 nickel-cadmium cells to be configured in series for a nominal 12 volt battery. The voltage of a nickel-cadmium cell remains relatively stable until the cell is almost completely discharged, where the voltage drops off dramatically. Nickel-cadmium batteries can accept charge rates as high as C/1, and are tolerant of continuous overcharge up to a C/15 rate. Nickel-cadmium batteries are commonly subdivided in to two primary types; *sintered plate* and *pocket plate*.

Sintered Plate Ni-Cads

Sintered plate nickel cadmium batteries are commonly used in electrical test equipment and consumer electronic devices. The batteries are designed by heat processing the active materials and rolling them into metallic case. The electrolyte in sintered plate nickel-cadmium batteries is immobilized, preventing leakage, allowing any orientation for installation. The main disadvantage of sintered plate designs is the so called 'memory effect', in which a battery that is repeatedly discharged to only a percentage of its rated capacity will eventually 'memorize' this cycle pattern, and will limit further discharge resulting in loss of capacity. In some cases, the 'memory effect' can be erased by conducting special charge and discharge cycles, regaining some of its initial rated capacity.

Pocket Plate Ni-Cads

Large nickel cadmium batteries used in remote telecommunications systems and other commercial applications are typically of a flooded design, called flooded *pocket plate*. Similar to flooded lead-acid designs, these batteries require periodic water additions, however, the electrolyte is an alkaline solution of potassium hydroxide, instead of a sulfuric acid solution. These batteries can withstand deep discharges and temperature extremes much better than lead-acid batteries, and they do not experience the 'memory effect' associated with sintered plate Ni-Cads. The main disadvantage of pocket plate nickel cadmium batteries is their high initial cost, however their long lifetimes can result in the lowest life cycle cost battery for some PV applications.

Battery Strengths and Weaknesses

Each battery type has design and performance features suited for particular applications. Again, no one type of battery is ideal for a PV system applications. The designer must consider the advantages and disadvantages of different batteries with respect to the requirements of a particular application. Some of the considerations include lifetime, deep cycle performance, tolerance to high temperatures and overcharge, maintenance and many others. Table 3 summarizes some of the key characteristics of the different battery types discussed in the preceding section.

Table 3. Battery Characteristics

Battery Type	Advantages	Disadvantages
Flooded Lead-Acid		
Lead-Antimony	low cost, wide availability, good deep cycle and high temperature performance, can replenish electrolyte	high water loss and maintenance
Lead-Calcium Open Vent	low cost, wide availability, low water loss, can replenish electrolyte	poor deep cycle performance, intolerant to high temperatures and overcharge
Lead-Calcium Sealed Vent	low cost, wide availability, low water loss	poor deep cycle performance, intolerant to high temperatures and overcharge, can not replenish electrolyte
Lead Antimony/Calcium Hybrid	medium cost, low water loss	limited availability, potential for stratification
Captive Electrolyte Lead-Acid		
Gelled	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Absorbed Glass Mat	medium cost, little or no maintenance, less susceptible to freezing, install in any orientation	fair deep cycle performance, intolerant to overcharge and high temperatures, limited availability
Nickel-Cadmium		
Sealed Sintered-Plate	wide availability, excellent low and high temperature performance, maintenance free	only available in low capacities, high cost, suffer from ‘memory’ effect
Flooded Pocket-Plate	excellent deep cycle and low and high temperature performance, tolerance to overcharge	limited availability, high cost, water additions required

Battery Performance Characteristics

Terminology and Definitions

Ampere-Hour (Ah): The common unit of measure for a battery's electrical storage capacity, obtained by integrating the discharge current in amperes over a specific time period. An ampere-hour is equal to the transfer of one-ampere over one-hour, equal to 3600 coulombs of charge. For example, a battery which delivers 5-amps for 20-hours is said to have delivered 100 ampere-hours.

Capacity: A measure of a battery's ability to store or deliver electrical energy, commonly expressed in units of *ampere-hours*. Capacity is generally specified at a specific discharge rate, or over a certain time period. The capacity of a battery depends on several design factors including: the quantity of active material, the number, design and physical dimensions of the plates, and the electrolyte specific gravity. Operational factors affecting capacity include: the discharge rate, depth of discharge, cut off voltage, temperature, age and cycle history of the battery. Sometimes a battery's energy storage capacity is expressed in kilowatt-hours (kWh), which can be approximated by multiplying the rated capacity in ampere-hours by the nominal battery voltage and dividing the product by 1000. For example, a nominal 12 volt, 100 ampere-hour battery has an energy storage capacity of (12 x 100)/1000 = 1.2 kilowatt-hours. Figure 2 shows the effects of temperature and discharge rate on lead-acid battery capacity.

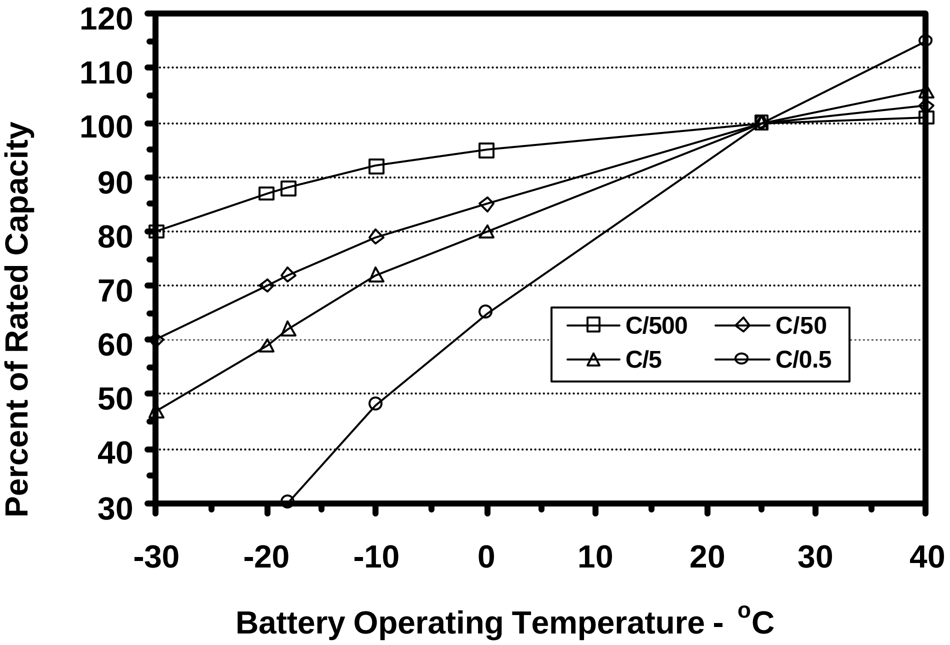


Figure 2. Effects on battery capacity

Cut Off Voltage: The lowest voltage which a battery system is allowed to reach in operation, defining the battery capacity at a specific discharge rate. Manufacturers often rate capacity to a specific cut off, or end of discharge voltage at a defined discharge rate. If the same cut off voltage is specified for different rates, the capacity will generally be higher at the lower discharge rate.

Cycle: Refers to a discharge to a given depth of discharge followed by a complete recharge. A 100 percent depth of discharge cycle provides a measure of the total battery capacity.

Discharge: The process when a battery delivers current, quantified by the discharge current or rate. Discharge of a lead-acid battery involves the conversion of lead, lead dioxide and sulfuric acid to lead sulfate and water.

Charge: The process when a battery receives or accepts current, quantified by the charge current or rate. Charging of a lead-acid battery involves the conversion of lead sulfate and water to lead, lead dioxide and sulfuric acid.

Rate of Charge/Discharge: The rate of charge or discharge of a battery is expressed as a ratio of the nominal battery capacity to the charge or discharge time period in hours. For example, a 4-amp discharge for a nominal 100 ampere-hour battery would be considered a C/20 discharge rate.

Negative (-): Referring to the lower potential point in a dc electrical circuit, the negative battery terminal is the point from which electrons or the current flows during discharge.

Positive (+): Referring to the higher potential point in a dc electrical circuit, the positive battery terminal is the point from which electrons or the current flows during charging.

Open Circuit Voltage: The voltage when a battery is at rest or steady-state, not during charge or discharge. Depending on the battery design, specific gravity and temperature, the open circuit voltage of a fully charged lead-acid battery is typically about 2.1-volts.

Battery Charging

Methods and procedures for battery charging vary considerably. In a stand-alone PV system, the ways in which a battery is charged are generally much different from the charging methods battery manufacturers use to rate battery performance. The various methods and considerations for battery charging in PV systems are discussed in the next section on battery charge controllers.

Battery manufacturers often refer to three modes of battery charging; *normal or bulk charge, finishing or float charge* and *equalizing charge*.

Bulk or Normal Charge: Bulk or normal charging is the initial portion of a charging cycle, performed at any charge rate which does not cause the cell voltage to exceed the gassing voltage. Bulk charging generally occurs up to between 80 and 90% state of charge.

Float or Finishing Charge: Once a battery is nearly fully charged, most of the active material in the battery has been converted to its original form, and voltage and or current regulation are generally required to limit the amount over overcharge supplied to the battery. Finish charging is usually conducted at low to medium charge rates.

Equalizing Charge: An equalizing or refreshing charge is used periodically to maintain consistency among individual cells. An equalizing charge generally consists of a current-limited charge to higher voltage limits than set for the finishing or float charge. For batteries deep discharged on a daily basis, an equalizing charge is recommended every one or two weeks. For batteries less severely discharged, equalizing may only be required every one or two months. An equalizing charge is typically maintained until the cell voltages and specific gravities remain consistent for a few hours.

Battery Discharging

Depth of Discharge (DOD): The depth of discharge (DOD) of a battery is defined as the percentage of capacity that has been withdrawn from a battery compared to the total fully charged capacity. By definition, the depth of discharge and *state of charge* of a battery add to 100 percent. The two common qualifiers for depth of discharge in PV systems are the *allowable* or *maximum DOD* and the a*verage daily DOD* and are described as follows:

> ***Allowable DOD:*** The maximum percentage of full-rated *capacity* that can be withdrawn from a battery is known as its allowable depth of discharge. The allowable DOD is the maximum discharge limit for a battery, generally dictated by the *cut off voltage* and *discharge rate.* In stand-alone PV systems, the *low voltage load disconnect* (LVD) set point of the battery charge controller dictates the allowable DOD limit at a given discharge rate. Furthermore, the allowable DOD is generally a seasonal deficit, resulting from low insolation, low temperatures and/or excessive load usage. Depending on the type of battery used in a PV system, the design allowable depth of discharge may be as high as 80% for deep cycle, motive power batteries, to as low as 15-25% if SLI batteries are used. The allowable DOD is related to the *autonomy*, in terms of the *capacity* required to operate the system loads for a given number of days without energy from the PV array. A system design with a lower allowable DOD will result in a shorter autonomy period. As discussed earlier, if the internal temperature of a battery reaches the freezing point of the electrolyte, the electrolyte can freeze and expand, causing irreversible damage to the battery. In a fully charged lead-acid battery, the electrolyte is approximately 35% by weight and the freezing point is quite low (approximately -60 ^{o}C). As a lead-acid battery is discharged, the becomes diluted, so the concentration of acid decreases and the concentration of water increases as the freezing point approaches the freezing point of water, 0 ^{o}C.
>
> ***Average Daily DOD:*** The average daily depth of discharge is the percentage of the full-rated *capacity* that is withdrawn from a battery with the *average daily load* profile. If the load varies seasonally, for example in a PV lighting system, the average daily DOD will be greater in the winter months due to the longer nightly load operation period. For PV systems with a constant daily load, the average daily DOD is generally greater in the winter due to lower battery temperature and lower rated capacity. Depending on the *rated capacity* and the *average daily load* energy, the average daily DOD may vary between only a few percent in systems designed with a lot of autonomy, or as high as 50 percent for marginally sized battery systems. The average daily DOD is inversely related to autonomy; meaning that systems designed for longer autonomy periods (more capacity) have a lower average daily DOD.

State of Charge (SOC): The state of charge (SOC) is defined as the amount of energy in a battery, expressed as a percentage of the energy stored in a fully charged battery. Discharging a battery results in a decrease in state of charge, while charging results in an increase in state of charge. A battery that has had three quarters of its capacity removed, or been discharged 75 percent, is said to be at 25 percent state of charge. Figure 3 shows the seasonal variation in battery *state of charge* and *depth of discharge*.

Autonomy: Generally expressed as the days of storage in a stand-alone PV system, autonomy refers to the time a fully charged battery can supply energy to the systems loads when there is no energy supplied by the PV array. For common, less critical PV applications autonomy periods are typically between two and six days. For critical applications involving an essential load or public safety, or where weather patterns dictate, autonomy periods may be greater than ten days. Longer autonomy periods generally result in a

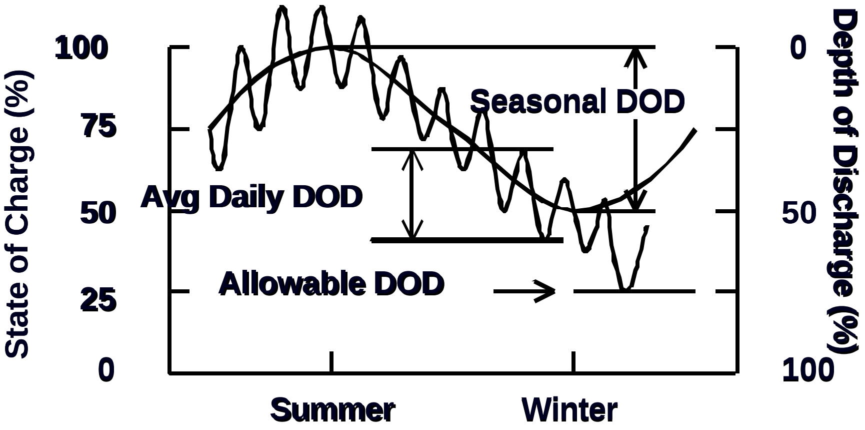


Figure 3. Battery state of charge

lower average daily DOD and lower the probability that the allowable (maximum) DOD or minimum load voltage is reached.

Self Discharge Rate: In open-circuit mode without any charge or discharge current, a battery undergoes a reduction in state of charge, due to internal mechanisms and losses within the battery. Different battery types have different self discharge rates, the most significant factor being the active materials and grid alloying elements used in the design. Higher temperatures result in higher discharge rates particularly for lead-antimony designs as shown in Figure 4.

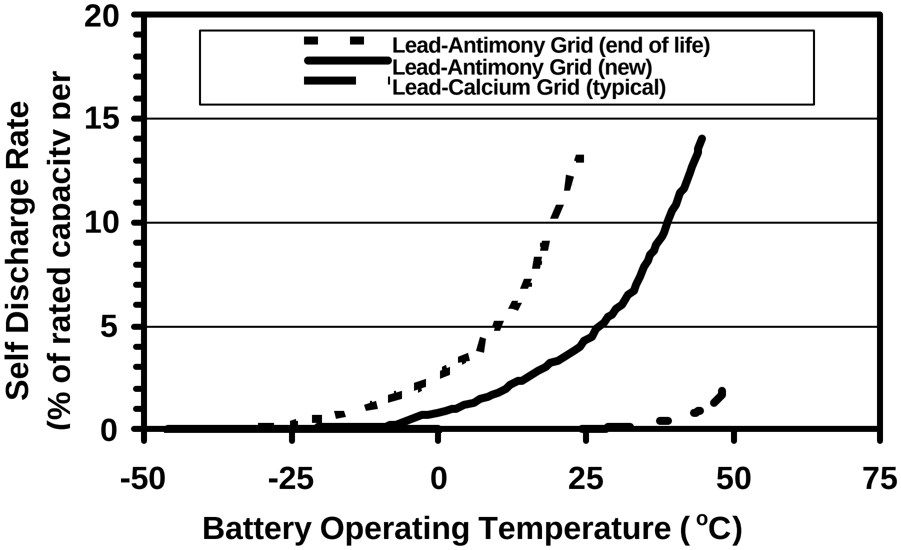


Figure 4. Battery self-discharge

Battery Lifetime: Battery lifetime is dependent upon a number of design and operational factors, including the components and materials of battery construction, temperature, frequency and depth of discharges, average state of charge and charging methods. As long as a battery is not overcharged, overdischarged or operated at excessive temperatures, the lifetime of a battery is proportionate to its average state of charge.

A typical flooded lead-acid battery that is maintained above 90 percent state of charge will provide two to three times more full charge/discharge cycles than a battery allowed to reach 50 percent state of charge before recharging. This suggests limiting the allowable and average daily DOD to prolong battery life.

Lifetime can be expressed in terms of *cycles* or *years*, depending upon the particular type of battery and its intended application. Exact quantification of battery life is difficult due to the number of variables involved, and generally requires battery test results under similar operating conditions. Battery manufacturers often do not rate battery performance under the conditions of charge and discharge experienced in PV systems.

Temperature Effects: For an electrochemical cell such as a battery, temperature has important effects on performance. Generally, as the temperature increases by 10^{o}C the rate of an electrochemical reaction doubles, resulting in statements from battery manufacturers that battery life decreases by a factor of two for every 10^{o} C increase in average operating temperature. Higher operating temperatures accelerate corrosion of the positive plate grids, resulting in greater gassing and electrolyte loss. Lower operating temperatures generally increase battery life. However, the capacity is reduced significantly at lower temperatures, particularly for lead-acid batteries. When severe temperature variations from room temperatures exist, batteries are located in an insulated or other temperature-regulated enclosure to minimize battery temperature swings.

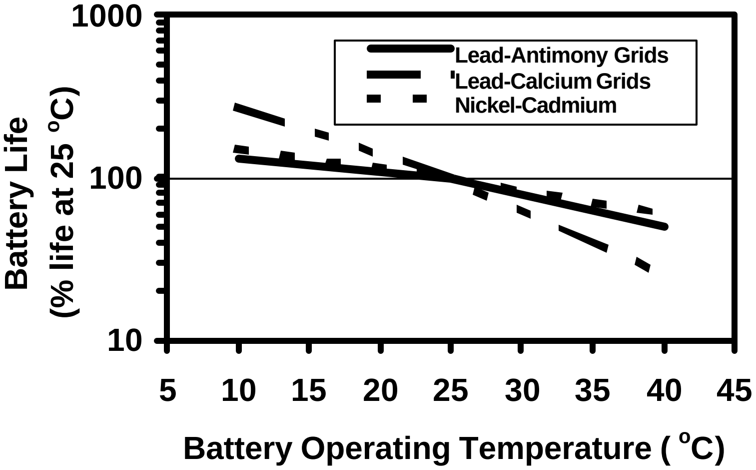


Figure 5. Temperature effects on battery life

Effects of Discharge Rates: The higher the discharge rate or current, the lower the capacity that can be withdrawn from a battery to a specific allowable DOD or cut off voltage. Higher discharge rates also result in the voltage under load to be lower than with lower discharge rates, sometimes affecting the selection of the low voltage load disconnect set point. At the same battery voltage the lower the discharge rates, the lower the battery state of charge compared to higher discharge rates.

Corrosion: The electrochemical activity resulting from the immersion of two dissimilar metals in an electrolyte, or the direct contact of two dissimilar metals causing one material to undergo oxidation or lose electrons and causing the other material to undergo reduction, or gain electrons. Corrosion of the grids supporting the active material in a battery is an ongoing process and may ultimately dictate the battery's useful lifetime. Battery terminals may also experience corrosion due to the action of electrolyte gassing from the battery, and generally require periodic cleaning and tightening in flooded lead-acid types. Higher temperatures and the flow of electrical current between two dissimilar metals accelerates the corrosion process.

Battery Gassing and Overcharge Reaction

Gassing occurs in a battery during charging when the battery is nearly fully charged. At this point, essentially all of the active materials have been converted to their fully charged composition and the cell voltage rises sharply. The gas products are either recombined internal to the cell as in sealed or *valve regulated* batteries, or released through the cell *vents* in flooded batteries. In general, the overcharge or gassing reaction in batteries is irreversible, resulting in water loss. However in sealed lead-acid cells, an internal recombinant process permits the reforming of water from the hydrogen and oxygen gasses generated under normal charging conditions, allowing the battery to be sealed and requiring no electrolyte maintenance. All gassing reactions consume a portion of the charge current which can not be delivered on the subsequent discharge, thereby reducing the battery charging efficiency.

In both flooded lead-acid and nickel-cadmium batteries, gassing results in the formation of hydrogen at the negative plate and oxygen at the positive plate, requiring periodic water additions to replenish the electrolyte. The following electrochemical reactions show the overcharge process in typical lead-acid cell.

At the negative plate or electrode:

$$2H^+ + 2e^- \Rightarrow H_2$$

At the positive plate or electrode:

$$H_2O - 2e^- \Rightarrow \tfrac{1}{2}O_2 + 2H^+$$

Overall lead-acid cell overcharge reaction:

$$H_2O \Rightarrow H \; + \tfrac{1}{2}O_2$$

Following are the electrochemical reactions for a typical nickel-cadmium cell.

At the negative plate or electrode:

$$4H_2O + 4e^- \Rightarrow 2H_2 + 4OH^-$$

At the positive plate or electrode:

$$4OH^- \Rightarrow 2H_2O + O_2 + 4e^-$$

Overall nickel-cadmium cell overcharge reaction:

$$2H_2O \Rightarrow 2H_2 + O_2$$

Flooded Batteries Require Some Gassing

Some degree of gassing is required to agitate and prevent stratification of the electrolyte in flooded batteries. When a flooded lead-acid battery is charged, heavy sulfuric acid forms on the plates, and falls to the bottom of the battery. Over time, the electrolyte stratifies, developing greater acid concentrations at the bottom of the battery than at the top. If left unmixed, the reaction process would be different from the bottom to the top of the plates, greater corrosion would occur, and battery performance would be poor. By gently gassing flooded batteries, the electrolyte is mixed preventing electrolyte stratification. However, excessive gassing and overcharge dislodges active materials from the grids, reducing the battery life. Excessive gassing may also lead to higher temperatures, which accelerates corrosion of the grids and shortens battery life.

Captive Electrolyte Batteries Should Avoid Gassing

Gassing control is especially important for captive electrolyte or sealed batteries. These are not flooded, and electrolyte cannot be replaced if allowed to escape due to overcharging. For these types of batteries, the charging process should be controlled more carefully to avoid gassing.

Charge Regulation Voltage Affects Gassing

The charge regulation voltage, or the maximum voltage that a charge controller allows a battery to reach in operation plays an important part in battery gassing. Charge controllers are used in photovoltaic power systems to allow high rates of charging up to the gassing point, and then limit or disconnect the PV current to prevent overcharge. The highest voltage that batteries are allowed to reach determines in part how much gassing occurs. To limit gassing and electrolyte loss to acceptable levels, proper selection of the charge controller voltage regulation set point is critical in PV systems. If too low of a regulation voltage is used, the battery will be undercharged. If too high of a regulation voltage is used, the battery will be overcharged. Both under and overcharging will result in premature battery failure and loss of load in stand-alone PV systems. In general, sealed “maintenance free” valve-regulated batteries (using lead-calcium grids) should have lower charge regulation voltage set points than flooded deep cycling batteries (using lead-antimony grids).

Other Factors Affecting Battery Gassing

The onset of gassing in a lead-acid cell is not only determined by the cell voltage, but the temperature as well. As temperatures increase, the corresponding gassing voltage decreases for a particular battery. Regardless of the charge rate, the gassing voltage is the same, however gassing begins at a lower battery state of charge at higher charge rates. The grid design, whether lead-antimony or lead-calcium also affects gassing. Battery manufacturers should be consulted to determine the gassing voltages for specific designs. Figure 14 shows the relationships between cell voltage, state of charge, charge rate and temperature for a typical lead-acid cell with lead-antimony grids.

By examining Figure 6, one can see that at 27 ^{o}C and at a charge rate of C/20, the gassing voltage of about 2.35 volts per cell is reached at about 90% state of charge. At a charge rate of C/5 at 27 ^{o}C, the gassing voltage is reached at about 75% state of charge. At a battery temperature of 0 ^{o}C the gassing voltage increases to about 2.5 volt per cell, or 15 volts for a nominal 12 volt battery. The effects of temperature on the gassing voltage is the reason the charge regulation voltage is sometimes temperature compensated - to fully charge batteries in cold weather and to limit overcharge during warm weather. This type of information is needed to properly select battery charge controller voltage regulation set points in order to limit the amount of gassing for a specific battery design and operational conditions.

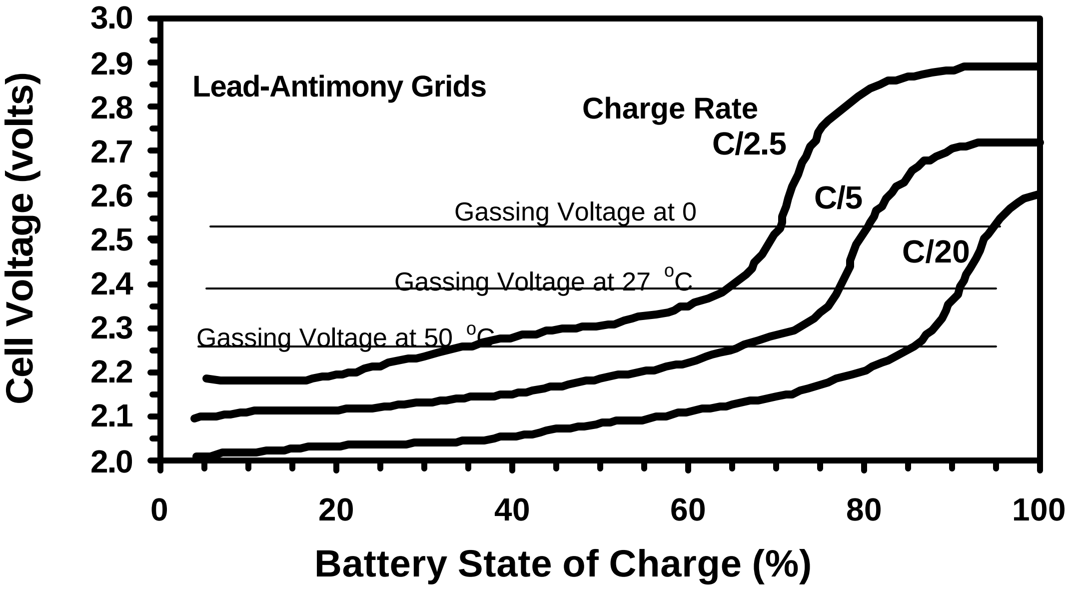


Figure 6. Lead-acid cell charging voltage

Some recommended ranges for charge regulation voltages (at 25 °C) for different battery types used in PV systems are presented in Table 10-4 below. These values are typical of voltage regulation set points for battery charge controllers used in small PV systems. These recommendations are meant to be only general in nature, and specific battery manufacturers should be consulted for their suggested values.

Table 3. Recommended Charge Regulation Voltages

	Battery Type			
Charge Regulation Voltage at 25 °C	Flooded Lead-Antimony	Flooded Lead-Calcium	Sealed, Valve Regulated Lead-Acid	Flooded Pocket Plate Nickel-Cadmium
Per nominal 12 volt battery	14.4 - 14.8	14.0 - 14.4	14.0 - 14.4	14.5 - 15.0
Per Cell	2.40 - 2.47	2.33 - 2.40	2.33 - 2.40	1.45 - 1.50

The charge regulation voltage ranges presented in Table 10-4 are much higher than the typical charge regulation values often presented in manufacturer’s literature. This is because battery manufacturers often speak of regulation voltage in terms of the *float voltage*, or the voltage limit suggested for when batteries are *float charged* for extended periods (for example, in un-interruptible power supply (UPS) systems). In these and many other commercial battery applications, batteries can be “trickle” or float charged for extended period, requiring a voltage low enough to limit gassing. Typical float voltages are between 13.5 and 13.8 volts for a nominal 12 volt battery, or between 2.25 and 2.30 volts for a single cell.

In a PV system however, the battery must be recharged within a limited time (usually during sunlight hours), requiring that the regulation voltage be much higher than the manufacturer’s float voltage to ensure that the battery is fully recharged. If charge regulation voltages in a typical PV system were set at the manufacturer’s recommended float voltage, the batteries would never be fully charged.

Battery System Design and Selection Criteria

Battery system design and selection criteria involves many decisions and trade offs. Choosing the right battery for a PV application depends on many factors. While no specific battery is appropriate for all PV applications, common sense and a careful review of the battery literature with respect to the particular application needs will help the designer narrow the choice. Some decisions on battery selection may be easy to arrive at, such as physical properties, while other decisions will be much more difficult and may involve making tradeoffs between desirable and undesirable battery features. With the proper application of this knowledge, designers should be able to differentiate among battery types and gain some application experience with batteries they are familiar with. Table 4 summarizes some of the considerations in battery selection and design.

Table 4. Battery Selection Criteria

- Type of system and mode of operation
- Charging characteristics; internal resistance
- Required days of storage (autonomy)
- Amount and variability of discharge current
- Maximum allowable depth of discharge
- Daily depth of discharge requirements
- Accessibility of location
- Temperature and environmental conditions
- Cyclic life and/or calendar life in years
- Maintenance requirements
- Sealed or unsealed
- Self-discharge rate
- Maximum cell capacity
- Energy storage density
- Size and weight
- Gassing characteristics
- Susceptibility to freezing
- Susceptibility to sulfation
- Electrolyte concentration
- Availability of auxiliary hardware
- Terminal configuration
- Reputation of manufacturer
- Cost and warranty.

Battery Subsystem Design

Once a particular type of battery has been selected, the designer must consider how best to configure and maintain the battery for optimal performance. Considerations in battery subsystem design include the number of batteries is series and parallel, over-current and disconnect requirements, and selection of the proper wire sizes and types.

Connecting Batteries in Series

Batteries connected in a series circuit have only one path for the *current* to flow. Batteries are arranged in series by connecting the *negative* terminal of the first battery to the *positive* terminal of the second battery, the negative of the second battery to the positive of the third battery, and so on for as many batteries or cells in the series string. For similar batteries connected in series, the total *voltage* is the sum of the individual battery voltages, and the total *capacity* is the same as for one battery. If batteries or cells with different capacities are connected in series, the capacity of the string is limited to the lower battery capacity. Figure 7 illustrates the series connection of two similar batteries.

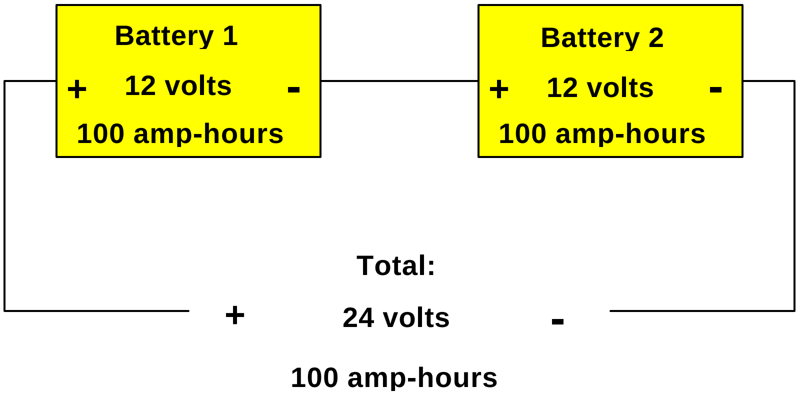


Figure 7. Series connected batteries

Connecting Batteries in Parallel

Batteries connected in *parallel* have more than one path for current to flow, depending on the number of parallel branches. Batteries (or series strings of batteries or cells) are arranged in parallel by connecting all of the *positive* terminals to one conductor and all of the *negative* terminals to another conductor. For similar batteries connected in parallel, the *voltage* across the entire circuit is the same as the voltage across the individual parallel branches, and the overall *capacity* is sum of the parallel branch capacities. Figure 8 illustrates the parallel connection of two similar batteries.

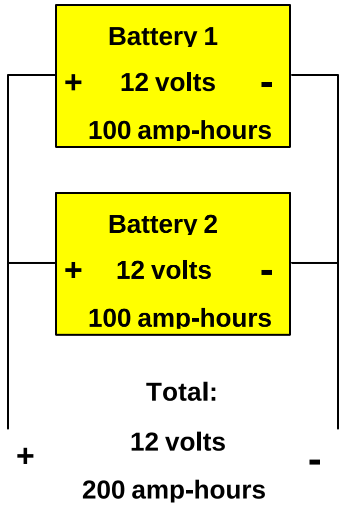


Figure 8. Parallel connected batteries

Series vs. Parallel Battery Connections

In general, battery manufacturers recommend that their batteries be operated in as few parallel strings as possible. If too many parallel connections are made in a battery bank, slight voltage differences between the parallel strings will occur due to the length, resistance and integrity of the connections. The result of these voltage differences can lead to inconsistencies in the treatment received by each battery (cell) in the bank, potentially causing unequal capacities within the bank. The parallel strings with the lowest circuit resistance to the charging source will generally be exercised to a greater extent than the parallel groups of batteries with greater circuit resistance to the charging source.   The batteries in parallel strings which receive less charge may begin to sulfate prematurely.

The battery capacity requirements and the size and voltage of the battery selected dictate the series and parallel connections required for a given PV application. For PV systems with larger capacity requirements, larger cells, generally in nominal 2-volt cells for lead-acid, may allow the batteries to be configured in one series string rather than in several parallel strings. When batteries must be configured in parallel, the external connection between the battery bank and the PV power system should be made from the positive and negative terminals on opposite sides of the battery bank to improve the equalization of charge and discharge from the bank (Figure 9).

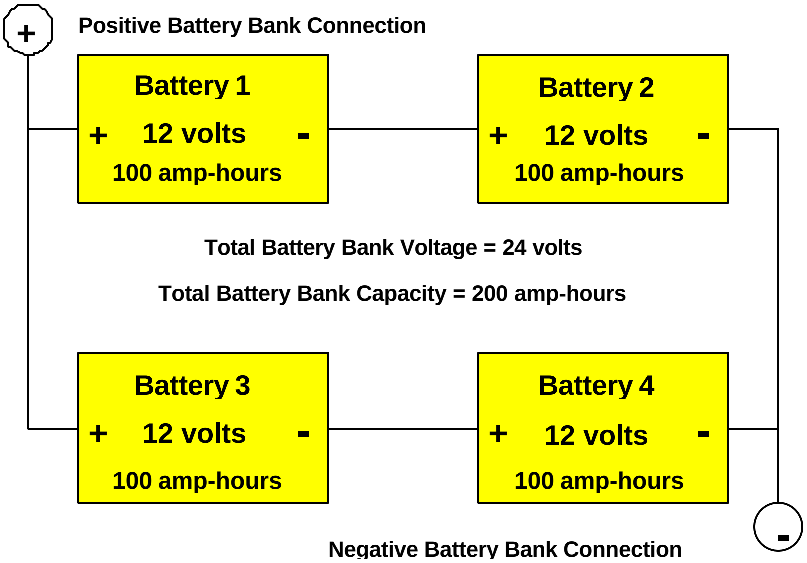


Figure 9. Parallel connections

Battery Bank Voltage Selection

Battery bank voltage selection is often dictated by load voltage requirements, most often 12 or 24 volts for small remote stand-alone PV systems. For larger loads requiring a larger PV array, it is sometimes prudent to go higher voltages if possible to lower the system currents. For example, a 120 watt dc load operating from a 12 volt battery draws 10 amps, however a 120 watt load operating from a 24 volt battery only draws 5 amps. Lower system currents minimize the size and cost of conductors, fuses, disconnects and other current handling components in the PV system.

Battery Conductor Selection

Conductors connecting the battery to other circuits and components in a PV system must be selected based on the current or ampacity requirements, voltage drop limitations and the environmental conditions. Conductors should be adequately sized to handle at least 125% of the maximum current, and limit the voltage drop to acceptable levels (generally less than 5%) between the battery and other components in the system at the peak rated currents. Conductor insulating materials should be selected based on temperature, moisture resistance or other application needs. Particular attention should be paid to selecting adequate size conductors for the high currents expected between the battery and inverter where applicable.

If too small of conductors are used between the PV array, charge controller and battery, the series resistance and resulting voltage drops may force the PV array to operate at a fraction of the array peak rated current. As a result, the charging effectiveness of the PV array is reduced, requiring more modules to do the job. In many cases, the batteries in systems with excessive voltage drops will not be fully recharged. Note that voltage drop limitations generally dictate larger conductor sizes than the sizes required to handle the current alone, particularly in low voltage systems (12 - 24 volts dc).

Overcurrent and Disconnect Requirements

Batteries can deliver thousands of amperes under short circuit conditions, potentially causing explosions, fires, burns, shock and equipment damage. For these reasons, proper dc rated overcurrent and disconnect protection devices are required on all PV battery systems. Fuses or circuit breakers used for overcurrent protection must not only be able to operate properly under 'normal' high currents resulting from load problems, but must also operate under battery short-circuit conditions. The ampere interrupt rating (AIR) for overcurrent devices must be considered with regard to the potential for battery system short-circuit currents, or the devices could fail with disastrous results. For ungrounded systems, disconnects are required on both the positive and negative conductors leading to and from the battery. For grounded systems, disconnect and overcurrent protection are only required on the ungrounded conductor. Figure 10-22 shows the overcurrent and disconnect requirements for batteries in PV systems.

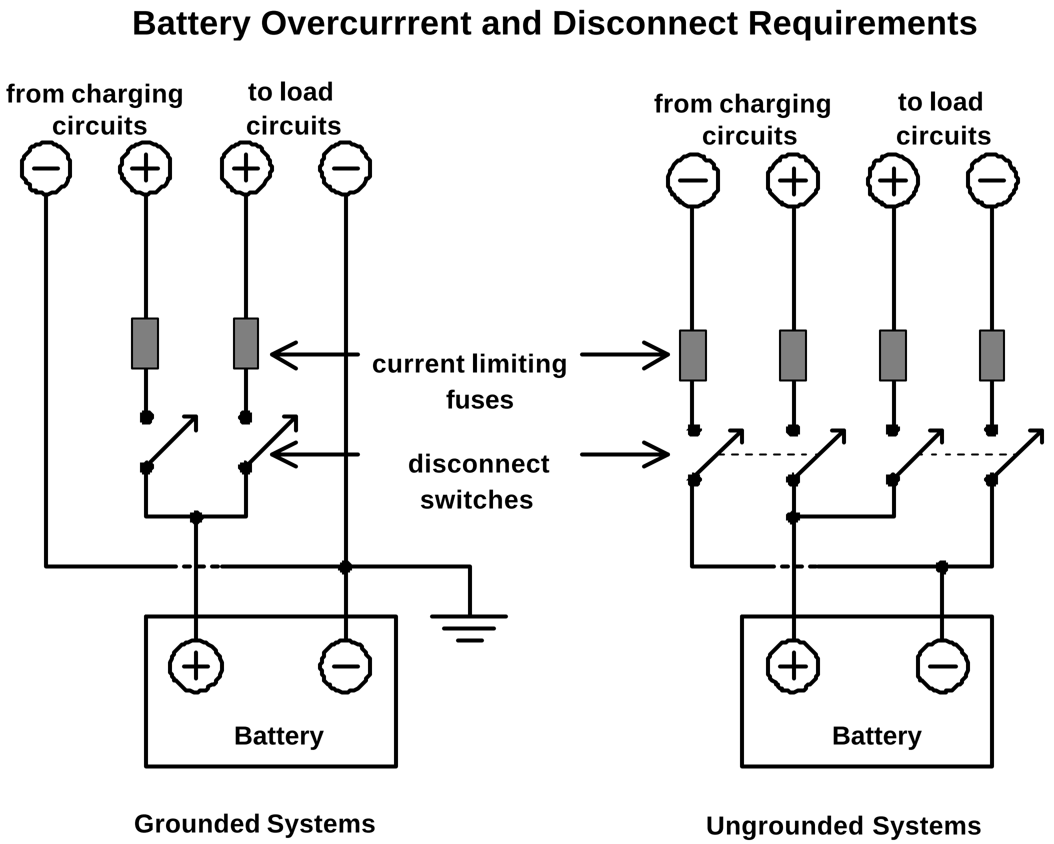


Figure 10. Battery circuit requirements

Battery Auxiliary Equipment

Battery auxiliary equipment includes any systems or other hardware necessary to safely and effectively operate a battery system. Some of the more important battery auxiliary systems and equipment are discussed below.

Enclosures

Batteries are generally required by local electrical codes and safety standards to be installed in an enclosure separated from controls or other PV system components. The enclosure may also be insulated, or may have active or passive cooling/heating mechanisms to protect the batteries from excessive temperatures. Battery enclosures must be of sufficient size and strength hold the batteries, and can be located below ground if needed to prevent freezing. If the enclosure is located above ground, care should be taken to limit the direct exposure to sunlight, or some type of shading or reflective coating should be provided.

Passive Cooling Enclosures

We have shown that temperature is a critical factor affecting battery performance and life expectancy. Any actions taken by the system designer to reduce temperature swings will be rewarded with better battery performance, longer life, and lower maintenance.

One approach to moderating the influence of ambient temperature swings on battery temperature is the use of passive cooling enclosures, without the need for active components such as motors, fans or air conditioners. The use of active temperature regulation means generally requires additional electrical power, and adds unnecessarily to the complexity, size and cost of the PV system. By using a thermodynamically passive approach, maximum benefits are gained with minimal complexity and maximum reliability -- key features of any PV system installation.

Ventilation

Batteries often produce toxic and explosive mixtures of gasses, namely hydrogen, and adequate ventilation of the battery enclosure is required. In most cases, passive ventilation techniques such as vents or ducts may be sufficient. In some cases, fans may be required to provide mechanical ventilation. Required air change rates are based on maintaining minimum levels of hazardous gasses in the enclosure. Under no circumstances should batteries be kept in an unventilated area or located in an area frequented by personnel.

Catalytic Recombination Caps

A substitute for standard vented caps on lead-antimony batteries, catalytic recombination caps (CRCs) primary function is to reduce the electrolyte loss from the battery. CRCs contain particles of an element such as platinum or palladium, which surfaces adsorb the hydrogen generated from the battery during finishing and overcharge. The hydrogen is then recombined with oxygen in the CRC to form water, which drains back into the battery. During this recombination process, heat is released from the CRCs as the combination of hydrogen and oxygen to form water is an exothermic process. This means that temperature increases in CRCs can be used to detect the onset of gassing in the battery. If CRCs are found to be at significantly different temperatures during recharge (meaning some cells are gassing and others are not), an equalization charge may be required. The use of CRCs on open-vent, flooded lead-antimony batteries has proven to reduce electrolyte loss by as much as 50% in subtropical climates.

Battery Monitoring Systems

Monitoring and instrumentation for battery systems can range from simple analog meters to more sophistication data acquisition systems. Lower level monitoring of battery systems might include voltage and current meters or battery state of charge indicators, while higher level monitoring may include automated recording of voltage, current, temperature, specific gravity and water levels. For small stand-alone PV systems, monitoring of the battery condition is generally done only occasionally during routine maintenance checks, or by simple meters or indicators on the battery charge controller.

Battery Maintenance

The maintenance requirements for batteries varies significantly depending on the battery design and application. Maintenance considerations may include cleaning of cases, cables and terminals, tightening terminals, water additions, and performance checks. Performance checks may include specific gravity recordings, conductance readings, temperature measurements, cell voltage readings, or even a capacity test. Battery voltage and current readings during charging can aid in determining whether the battery charge controller is operating properly. If applicable, auxiliary systems such as ventilation, fire extinguishers and safety equipment may need to be inspected periodically.

Generally speaking, flooded lead-antimony batteries require the most maintenance in terms of water additions and cleaning. Sealed lead-acid batteries including gelled and AGM types remain relatively clean during operation and do not require water additions. Battery manufacturers often provide maintenance recommendations for the use of their battery.

Battery Test Equipment

The ability to measure and diagnose battery performance is an invaluable aid to users and operators of stand-alone PV systems. Following are two of the more common instruments used to test batteries.

Hydrometer

A hydrometer is an instrument used to measure the *specific gravity* of a solution, or the ratio of the solution density to the density of water. While the specific gravity of the electrolyte can be estimated from open-circuit voltage readings, a hydrometer provides a much more accurate measure. As discussed previously, the specific gravity of the electrolyte is related to the battery state of charge in lead-acid batteries.

Hydrometers may be constructed with a float ball using *Archimedes' principle*, or with a prism measuring the *refractive index* of the solution to determine specific gravity. In an Archimedes hydrometer, a bulb-type syringe extracts electrolyte from the battery cell. When the bulb is filled with electrolyte, a precision glass float in the bulb is subjected to a buoyant force equivalent to the weight of the electrolyte displaced. Graduations are marked on the sides of the glass float, calibrated to read specific gravity directly.

Hydrometer floats are only calibrated to give true readings at a specific temperature, typically 26.7 ^{o}C (80 ^{o}F). When measurements are taken from electrolyte at other temperatures, a correction factor must be applied. Regardless of the reference temperature of the hydrometer, a standard correction factor 0.004 specific gravity units, often referred to as “points”, must be applied for every 5.5 ^{o}C (10 ^{o}F) change from the reference temperature. Four “points” of specific gravity (0.004) are added to the hydrometer reading for every 5.5 ^{o}C (10 ^{o}F) increment above the reference temperature and four points are subtracted for every 5.5 ^{o}C (10 ^{o}F) increment below the reference temperature. When taking specific gravity measurements of batteries at temperatures significantly lower or higher than standard room temperatures, it is important that the temperature of the electrolyte be accurately measured to make the necessary corrections. When making specific gravity readings, the variations between cells are as important as the overall average of the readings.

Load Tester

A battery load tester is an instrument which draws current from a battery with an electrical load, while recording the voltage, usually done at high *discharge rates* for short periods. Although not designed to measure *capacity*, a load test may be used to determine the general health or consistency among batteries in a system. Load test data are generally expressed as a *discharge current* over a specific *time* period.

Battery Safety Considerations

Due to the hazardous materials and chemicals involved, and the amount of electrical energy which they store, batteries are potentially dangerous and must be handled and used with caution. Typical batteries used in stand-alone PV systems can deliver up to several thousand amps under short-circuit conditions, requiring special precautions. Depending on the size and location of a battery installation, certain safety precautions are be required.

Handling Electrolyte

The caustic sulfuric acid solution contained in lead-acid batteries can destroy clothing and burn the skin. For these reasons, protective clothing such as aprons and face shields should be worn by personnel working with batteries. To neutralize sulfuric acid spills or splashes on clothing, the spill should be rinsed immediately with a solution of baking soda or household ammonia and water. For nickel-cadmium batteries, the potassium hydroxide electrolyte can be neutralized with a vinegar and water solution. If electrolyte is accidentally splashed in the eyes, the eyes should be forced open and flooded with cool clean water for fifteen minutes. If acid electrolyte is taken internally, drink large quantities of water or milk, followed by milk of magnesia, beaten eggs or vegetable oil. Call a physician immediately.

If it is required that the electrolyte solution be prepared from concentrated acid and water, the acid should be poured slowly into the water while mixing. The water should never be poured into the acid. Appropriate non-metallic funnels and containers should be used when mixing and transferring electrolyte solutions.

Personnel Protection

When performing battery maintenance, personnel should wear protective clothing such as aprons, ventilation masks, goggles or face shields and gloves to protect from acid spills or splashes and fumes. If sulfuric acid comes into contact with skin or clothing, immediately flush the area with a solution of baking soda or ammonia and water. Safety showers and eye washes may be required where batteries are located in close access to personnel. As a good practice, some type of fire extinguisher should be located in close proximity to the battery area if possible. In some critical applications, automated fire sprinkler systems may be required to protect facilities and expensive load equipment. Jewelry on the hands and wrists should be removed, and properly insulated tools should be used to protect against inadvertent battery short-circuits.

Dangers of Explosion

During operation, batteries may produce explosive mixtures of hydrogen and oxygen gasses. Keep spark, flames, burning cigarettes, or other ignition sources away from batteries at all times. Explosive gasses may be present for several hours after a battery has been charged. Active or passive ventilation techniques are suggested and often required, depending on the number of batteries located in an enclosure and their gassing characteristics. The use of battery vent caps with a flame arrester feature lowers the possibility of a catastrophic battery explosion. Improper charging and excessive overcharging may increase the possibility of battery explosions. When making and breaking connections to a battery from a charging source or electrical load, ensure that the charger or load is switched off as to not create sparks or arcing during the connection.

Battery Disposal and Recycling

Batteries are considered hazardous items as they contain toxic materials such as lead, acids and plastics which can harm humans and the environment. For this reason, laws have been established which dictate the requirements for battery disposal and recycling. In most areas, batteries may be taken to the local landfill, where they are in turn taken to approved recycling centers. In some cases, battery manufacturers provide guidelines for battery disposal through local distributors, and may in fact recycle batteries themselves. Under no circumstances should a batteries be disposed of in landfills, or the electrolyte allowed to seep into the ground, or the battery burned.

BATTERY CHARGE CONTROLLERS IN PV SYSTEMS

The primary function of a charge controller in a stand-alone PV system is to maintain the battery at highest possible state of charge while protecting it from overcharge by the array and from overdischarge by the loads. Although some PV systems can be effectively designed without the use of charge control, any system that has unpredictable loads, user intervention, optimized or undersized battery storage (to minimize initial cost) typically requires a battery charge controller. The algorithm or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the load demands. Additional features such as temperature compensation, alarms, meters, remote voltage sense leads and special algorithms can enhance the ability of a charge controller to maintain the health and extend the lifetime of a battery, as well as providing an indication of operational status to the system caretaker.

Important functions of battery charge controllers and system controls are:

- ***Prevent Battery Overcharge:*** to limit the energy supplied to the battery by the PV array when the battery becomes fully charged.

- ***Prevent Battery Overdischarge:*** to disconnect the battery from electrical loads when the battery reaches low state of charge.

- ***Provide Load Control Functions:*** to automatically connect and disconnect an electrical load at a specified time, for example operating a lighting load from sunset to sunrise.

Overcharge Protection

A remote stand-alone photovoltaic system with battery storage is designed so that it will meet the system electrical load requirements under reasonably determined worst-case conditions, usually for the month of the year with the lowest insolation to load ratio. When the array is operating under good-to-excellent weather conditions (typically during summer), energy generated by the array often exceeds the electrical load demand. To prevent battery damage resulting from overcharge, a *charge controller* is used to protect the battery. A charge controller should prevent overcharge of a battery regardless of the system sizing/design and seasonal changes in the load profile, operating temperatures and solar insolation.

Charge regulation is the primary function of a battery charge controller, and perhaps the single most important issue related to battery performance and life. The purpose of a charge controller is to supply power to the battery in a manner which fully recharges the battery without overcharging. Without charge control, the current from the array will flow into a battery proportional to the irradiance, whether the battery needs charging or not. If the battery is fully charged, unregulated charging will cause the battery voltage to reach exceedingly high levels, causing severe gassing, electrolyte loss, internal heating and accelerated grid corrosion. In most cases if a battery is not protected from overcharge in PV system, premature failure of the battery and loss of load are likely to occur.

Charge controllers prevent excessive battery overcharge by interrupting or limiting the current flow from the array to the battery when the battery becomes fully charged. Charge regulation is most often accomplished by limiting the battery voltage to a maximum value, often referred to as the *voltage regulation (VR) set point*. Sometimes, other methods such as integrating the ampere-hours into and out of the battery are used. Depending on the regulation method, the current may be limited while maintaining the regulation voltage, or remain disconnected until the battery voltage drops to the *array reconnect voltage (ARV) set point*. A further discussion of charge regulation strategies set points is contained later in this chapter.

Overdischarge Protection

During periods of below average insolation and/or during periods of excessive electrical load usage, the energy produced by the PV array may not be sufficient enough to keep the battery fully recharged. When a battery is deeply discharged, the reaction in the battery occurs close to the grids, and weakens the bond between the active materials and the grids. When a battery is excessively discharged repeatedly, loss of capacity and life will eventually occur. To protect batteries from overdischarge, most charge controllers include an optional feature to disconnect the system loads once the battery reaches a low voltage or low state of charge condition.

In some cases, the electrical loads in a PV system must have sufficiently high enough voltage to operate. If batteries are too deeply discharged, the voltage falls below the operating range of the loads, and the loads may operate improperly or not at all. This is another important reason to limit battery overdischarge in PV systems.

Overdischarge protection in charge controllers is usually accomplished by open-circuiting the connection between the battery and electrical load when the battery reaches a pre-set or adjustable *low voltage load disconnect (LVD) set point*. Most charge controllers also have an indicator light or audible alarm to alert the system user/operator to the load disconnect condition. Once the battery is recharged to a certain level, the loads are again reconnected to a battery.

Non-critical system loads are generally always protected from overdischarging the battery by connection to the low voltage load disconnect circuitry of the charge controller. If the battery voltage falls to a low but safe level, a relay can open and disconnect the load, preventing further battery discharge. *Critical loads* can be connected directly to the battery, so that they are not automatically disconnected by the charge controller. However, the danger exists that these critical loads might overdischarge the battery. An alarm or other method of user feedback should be included to give information on the battery status if critical loads are connected directly to the battery.

Charge Controller Terminology and Definitions

Charge regulation is the primary function of a battery charge controller, and perhaps the single most important issue related to battery performance and life. The purpose of a charge controller is to supply power to the battery in a manner to fully recharge the battery without overcharging. Regulation or limiting the PV array current to a battery in a PV system may be accomplished by several methods. The most popular method is battery voltage sensing, however other methods such as amp hour integration are also employed. Generally, voltage regulation is accomplished by limiting the PV array current at a predefined charge regulation voltage. Depending on the regulation algorithm, the current may be limited while maintaining the regulation voltage, or remain disconnected until the battery voltage drops to the array reconnect set point.

While the specific regulation method or algorithm vary among charge controllers, all have basic parameters and characteristics. Charge controller manufacturer's data generally provides the limits of controller application such as PV and load currents, operating temperatures, parasitic losses, set points, and set point hysteresis values. In some cases the set points may be dependent upon the temperature of the battery and/or controller, and the magnitude of the battery current. A discussion of basic charge controller terminology follows:

Charge Controller Set Points

The battery voltage levels at which a charge controller performs control or switching functions are called the controller set points. Four basic control set points are defined for most charge controllers that have battery overcharge and overdischarge protection features. The voltage regulation (VR) and the array reconnect voltage (ARV) refer to the voltage set points at which the array is connected and disconnected from the battery. The low voltage load disconnect (LVD) and load reconnect voltage (LRV) refer to the voltage set points at which the load is disconnected from the battery to prevent overdischarge. Figure 12-1 shows the basic controller set points on a simplified diagram plotting battery voltage versus time for a charge and discharge cycle. A detailed discussion of each charge controller set point follows.

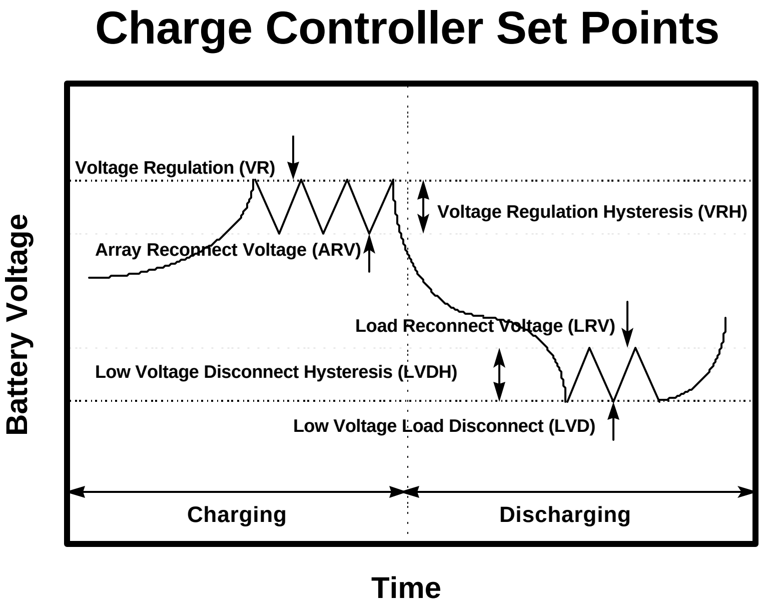


Figure 11. Controller set points

Voltage Regulation (VR) Set Point

The *voltage regulation (VR) set point* is one of the key specifications for charge controllers. The voltage regulation set point is defined as the maximum voltage that the charge controller allows the battery to reach, limiting the overcharge of the battery. Once the controller senses that the battery reaches the voltage regulation set point, the controller will either discontinue battery charging or begin to regulate (limit) the amount of current delivered to the battery. In some controller designs, dual regulation set points may be used. For example, a higher regulation voltage may be used for the first charge cycle of the day to provide a little battery overcharge, gassing and equalization, while a lower regulation voltage is used on subsequent cycles through the remainder of the day to effectively ‘float charge’ the battery.

Proper selection of the voltage regulation set point may depend on many factors, including the specific battery chemistry and design, sizes of the load and array with respect to the battery, operating temperatures, and electrolyte loss considerations. For flooded batteries, the regulation voltage should be selected at a point that allows the battery to achieve a minimal level of gassing. However, gassing should be avoided for sealed, valve-regulated lead-acid (VRLA) batteries. Temperature compensation of the voltage regulation set point is often incorporated in charge controller design, and is highly recommended for VRLA batteries and if battery temperatures exceed ± 5 ^{o}C from normal ambient temperatures (25 ^{o}C). A discussion on voltage regulation set point selection and temperature compensation are contained later in this chapter.

An important point to note about the voltage regulation set point is that the values required for optimal battery performance in stand-alone PV systems are generally much higher than the regulation or ‘float voltages’ recommended by battery manufacturers. This is because in a PV system, the battery must be recharged within a limited time period (during sunlight hours), while battery manufacturers generally allow for much longer recharge times when determining their optimal regulation voltage limits. By using a higher regulation voltage in PV systems, the battery can be recharged in a shorter time period, however some degree over overcharge and gassing will occur. The designer is faced selecting the optimal voltage regulation set point that maintains the highest possible battery state of charge without causing significant overcharge.

Array Reconnect Voltage (ARV) Set Point

In interrupting (on-off) type controllers, once the array current is disconnected at the voltage regulation set point, the battery voltage will begin to decrease. The rate at which the battery voltage decreases depends on many factors, including the charge rate prior to disconnect, and the discharge rate dictated by the electrical load. If the charge and discharge rates are high, the battery voltage will decrease at a greater rate than if these rates are lower. When the battery voltage decreases to a predefined voltage, the array is again reconnected to the battery to resume charging. This voltage at which the array is reconnected is defined as the *array reconnect voltage (ARV) set point*.

If the array were to remain disconnected for the rest of day after the regulation voltage was initially reached, the battery would not be fully recharged. By allowing the array to reconnect after the battery voltage reduces to a set value, the array current will ‘cycle’ into the battery in an on-off manner, disconnecting at the regulation voltage set point, and reconnecting at the array reconnect voltage set point. In this way, the battery will be brought up to a higher state of charge by ‘pulsing’ the array current into the battery.

It is important to note that for some controller designs, namely constant-voltage and pulse-width-modulated (PWM) types, there is no clearly distinguishable difference between the VR and ARV set points. In these designs, the array current is not regulated in a simple on-off or interrupting fashion, but is only limited as the battery voltage is held at a relatively constant value through the remainder of the day. A discussion on these types of controllers is included later in this chapter.

Voltage Regulation Hysteresis (VRH)

The voltage span or difference between the voltage regulation set point and the array reconnect voltage is often called the *voltage regulation hysteresis (VRH)*. The VRH is a major factor which determines the effectiveness of battery recharging for interrupting (on-off) type controllers. If the hysteresis is to great, the array current remains disconnected for long periods, effectively lowering the array energy utilization and making it very difficult to fully recharge the battery. If the regulation hysteresis is too small, the array will cycle on and off rapidly, perhaps damaging controllers which use electro-mechanical switching elements.

The designer must carefully determine the hysteresis values based on the system charge and discharge rates and the charging requirements of the particular battery.

Most interrupting (on-off) type controllers have hysteresis values between 0.4 and 1.4 volts for nominal 12 volt systems. For example, for a controller with a voltage regulation set point of 14.5 volts and a regulation hysteresis of 1.0 volt, the array reconnect voltage would be 13.5 volts. In general, a smaller regulation hysteresis is required for PV systems that do not have a daytime load.

Low Voltage Load Disconnect (LVD) Set Point

Overdischarging the battery can make it susceptible to freezing and shorten it's operating life. If battery voltage drops too low, due to prolonged bad weather for example, certain non-essential loads can be disconnected from the battery to prevent further discharge. This can be done using a *low voltage load disconnect (LVD)* device connected between the battery and non-essential loads. The LVD is either a relay or a solid-state switch that interrupts the current from the battery to the load, and is included as part of most controller designs. In some cases, the low voltage load disconnect unit may be a separate unit from the main charge controller.

In controllers or controls incorporating a load disconnect feature, the *low voltage load disconnect (LVD) set point* is the voltage at which the load is disconnected from the battery to prevent overdischarge. *The LVD set point defines the actual allowable maximum depth-of-discharge and available capacity of the battery operating in a PV system.* The available capacity must be carefully estimated in the PV system design and sizing process using the actual depth of discharge dictated by the LVD set point.

In more sophisticated deigns, a hierarchy of load importance can be established, and the more critical loads can be shed at progressively lower battery voltages. Very critical loads can remain connected directly to the battery so their operation is not interrupted.

The proper LVD set point will maintain a healthy battery while providing the maximum battery capacity and load availability. To determine the proper load disconnect voltage, the designer must consider the rate at which the battery is discharged. Because the battery voltage is affected by the rate of discharge, a lower load disconnect voltage set point is needed for high discharge rates to achieve the same depth of discharge limit. In general, the low discharge rates in most small stand-alone PV systems do not have a significant effect on the battery voltage. Typical LVD values used are between 11.0 and 11.5 volts, which corresponds to about 75-90% depth of discharge for most nominal 12 volt lead-acid batteries at discharge rates lower than C/30.

A word of caution is in order when selecting the low voltage load disconnect set point. Battery manufacturers rate discharge capacity to a specified cut-off voltage which corresponds to 100% depth of discharge for the battery. For lead-acid batteries, this cut-off voltage is typically 10.5 volts for a nominal 12 volt battery (1.75 volts per cell). In PV systems, we never want to allow a battery to be completely discharged as this will shorten it's service life. In general, the low voltage load disconnect set point in PV systems is selected to discharge the battery to no greater than 75-80% depth of discharge.

In cases where starting (SLI) batteries are used or it is otherwise desired to limit the battery depth of discharge to prevent freezing or prolong cycle life, a higher LVD set point may be desired. To protect the battery from freezing, the LVD set point may be temperature compensated in some cases to increase the load disconnect voltage automatically with decreasing battery temperature.

To properly specify the LVD set point in PV systems, the designer must know how the battery voltage is affected at different states of charge and discharge rates.   In a few designs, current compensation may be included in the LVD circuitry to lower the LVD set point with increasing discharge rates to effectively keep a consistent depth of discharge limit at which the LVD occurs.

Load Reconnect Voltage (LRV) Set Point

The battery voltage at which a controller allows the load to be reconnected to the battery is called the *load reconnect voltage (‘LRV)*. After the controller disconnects the load from the battery at the LVD set point, the battery voltage rises to it’s open-circuit voltage. When additional charge is provided by the array or a backup source, the battery voltage rises even more. At some point, the controller senses that the battery voltage and state of charge are high enough to reconnect the load, called the *load reconnect voltage set point*.

The selection of the load reconnect set point should be high enough to ensure that the battery has been somewhat recharged, while not to high as to sacrifice load availability by allowing the loads to be disconnected too long. Many controller designs effectively ‘lock out’ loads until the next day or when the controller senses that the array is again recharging the battery. Typically LVD set points used in small PV systems are between 12.5 and 13.0 volts for most nominal 12 volt lead-acid batteries. If the LRV set point is selected too low, the load may be reconnected before the battery has been charged, possibly cycling the load on and off, keeping the battery at low state of charge and shortening it’s lifetime.

As in the selection of the other controller set points, the designer must consider the charge rates for the loads and array and how these rates affect battery voltage at different states of charge.

Low Voltage Load Disconnect Hysteresis (LVDH)

The voltage span or difference between the LVD set point and the load reconnect voltage is called the *low voltage disconnect hysteresis (LVDH)*. If the LVDH is too small, the load may cycle on and off rapidly at low battery state-of-charge (SOC), possibly damaging the load or controller, and extending the time it takes to fully charge the battery. If the LVDH is too large, the load may remain off for extended periods until the array fully recharges the battery. With a large LVDH, battery health may be improved due to reduced battery cycling, but with a reduction in load availability. The proper LVDH selection for a given system will depend on load availability requirements, battery chemistry and size, and the PV and load currents.

Charge Controller Designs

Two basic methods exist for controlling or regulating the charging of a battery from a PV module or array - *shunt* and *series* regulation. While both of these methods are effectively used, each method may incorporate a number of variations that alter their basic performance and applicability. Simple designs interrupt or disconnect the array from the battery at regulation, while more sophisticated designs limit the current to the battery in a linear manner that maintains a high battery voltage.

The *algorithm* or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the electrical load demands. Most importantly, the controller algorithm defines the way in which PV array power is applied to the battery in the system. In general, interrupting on-off type controllers require a higher regulation set point to bring batteries up to full state of charge than controllers that limit the array current in a gradual manner.

Some of the more common design approaches for charge controllers are described in this section. Typical daily charging profiles for a few of the common types of controllers used in small PV lighting systems are presented in the next section.

Shunt Controller Designs

Since photovoltaic cells are current-limited by design (unlike batteries), PV modules and arrays can be short-circuited without any harm. The ability to short-circuit modules or an array is the basis of operation for shunt controllers.

Figure 12 shows an electrical design of a typical shunt type controller. The shunt controller regulates the charging of a battery from the PV array by short-circuiting the array internal to the controller. All shunt controllers must have a blocking diode in series between the battery and the shunt element to prevent the battery from short-circuiting when the array is regulating. Because there is some voltage drop between the array and controller and due to wiring and resistance of the shunt element, the array is never entirely short-circuited, resulting in some power dissipation within the controller. For this reason, most shunt controllers require a heat sink to dissipate power, and are generally limited to use in PV systems with array currents less than 20 amps.

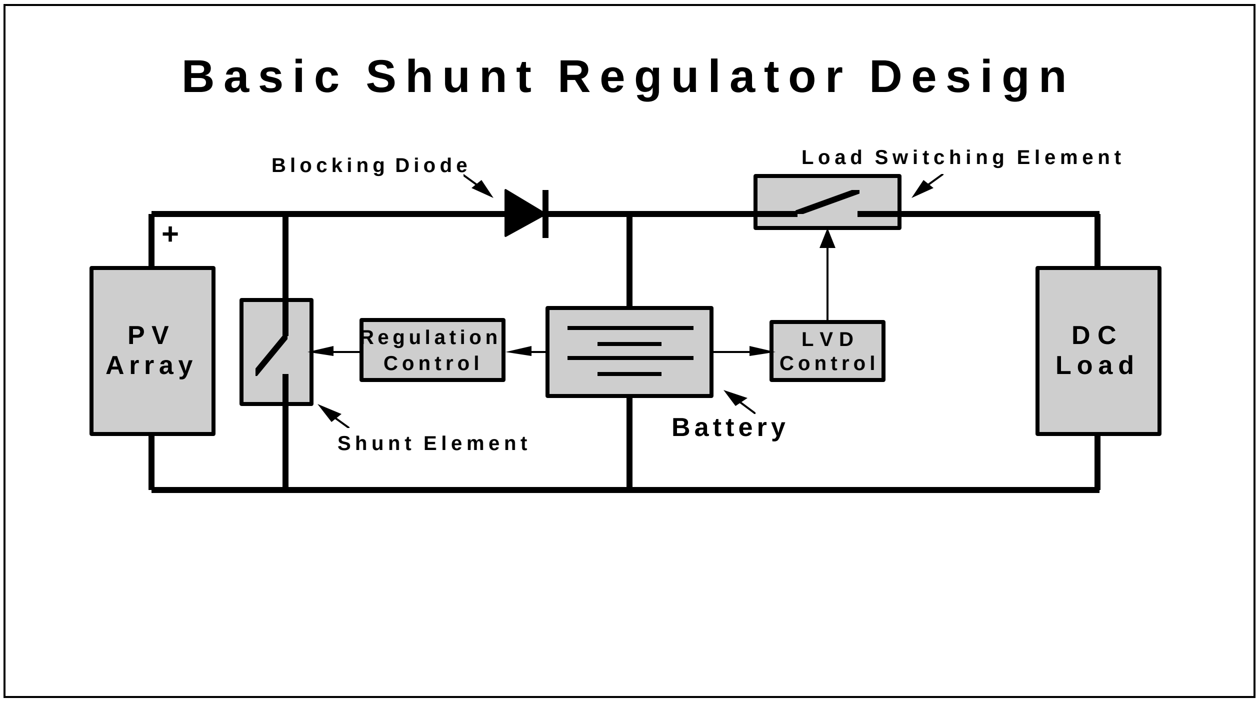


Figure 12. Shunt controller

The regulation element in shunt controllers is typically a power transistor or MOSFET, depending on the specific design. There are a couple of variations of the shunt controller design. The first is a simple interrupting, or on-off type controller design. The second type limits the array current in a gradual manner, by increasing the resistance of the shunt element as the battery reaches full state of charge. These two variations of the shunt controller are discussed next.

Shunt-Interrupting Design

The shunt-interrupting controller completely disconnects the array current in an interrupting or on-off fashion when the battery reaches the voltage regulation set point. When the battery decreases to the array reconnect voltage, the controller connects the array to resume charging the battery. This cycling between the regulation voltage and array reconnect voltage is why these controllers are often called ‘on-off’ or ‘pulsing’ controllers. Shunt-interrupting controllers are widely available and are low cost, however they are generally limited to use in systems with array currents less than 20 amps due to heat dissipation requirements. In general, on-off shunt controllers consume less power than series type controllers that use relays (discussed later), so they are best suited for small systems where even minor parasitic losses become a significant part of the system load.

Shunt-interrupting charge controllers can be used on all battery types, however the way in which they apply power to the battery may not be optimal for all battery designs. In general, constant-voltage, PWM or linear controller designs are recommended by manufacturers of gelled and AGM lead-acid batteries.   However, shunt-interrupting controllers are simple, low cost and perform well in most small stand-alone PV systems.

Shunt-Linear Design

Once a battery becomes nearly fully charged, a shunt-linear controller maintains the battery at near a fixed voltage by gradually shunting the array through a semiconductor regulation element. In some designs, a comparator circuit in the controller senses the battery voltage, and makes corresponding adjustments to the impedance of the shunt element, thus regulating the array current.   In other designs, simple Zener power diodes are used, which are the limiting factor in the cost and power ratings for these controllers. There is generally more heat dissipation in a shunt-linear controllers than in shunt-interrupting types.

Shunt-linear controllers are popular for use with sealed VRLA batteries. This algorithm applies power to the battery in a preferential method for these types of batteries, by limiting the current while holding the battery at the regulation voltage.

Series Controller Designs

As the name implies, this type of controller works in series between the array and battery, rather than in parallel as for the shunt controller. There are several variations to the series type controller, all of which use some type of control or regulation element in series between the array and the battery. While this type of controller is commonly used in small PV systems, it is also the practical choice for larger systems due to the current limitations of shunt controllers.

Figure 13 shows an electrical design of a typical series type controller. In a series controller design, a relay or solid-state switch either opens the circuit between the array and the battery to discontinuing charging, or limits the current in a series-linear manner to hold the battery voltage at a high value. In the simpler series-interrupting design, the controller reconnects the array to the battery once the battery falls to the array reconnect voltage set point. As these on-off charge cycles continue, the ‘on’ time becoming shorter and shorter as the battery becomes fully charged.

Because the series controller open-circuits rather than short-circuits the array as in shunt-controllers, no blocking diode is needed to prevent the battery from short-circuiting when the controller regulates.

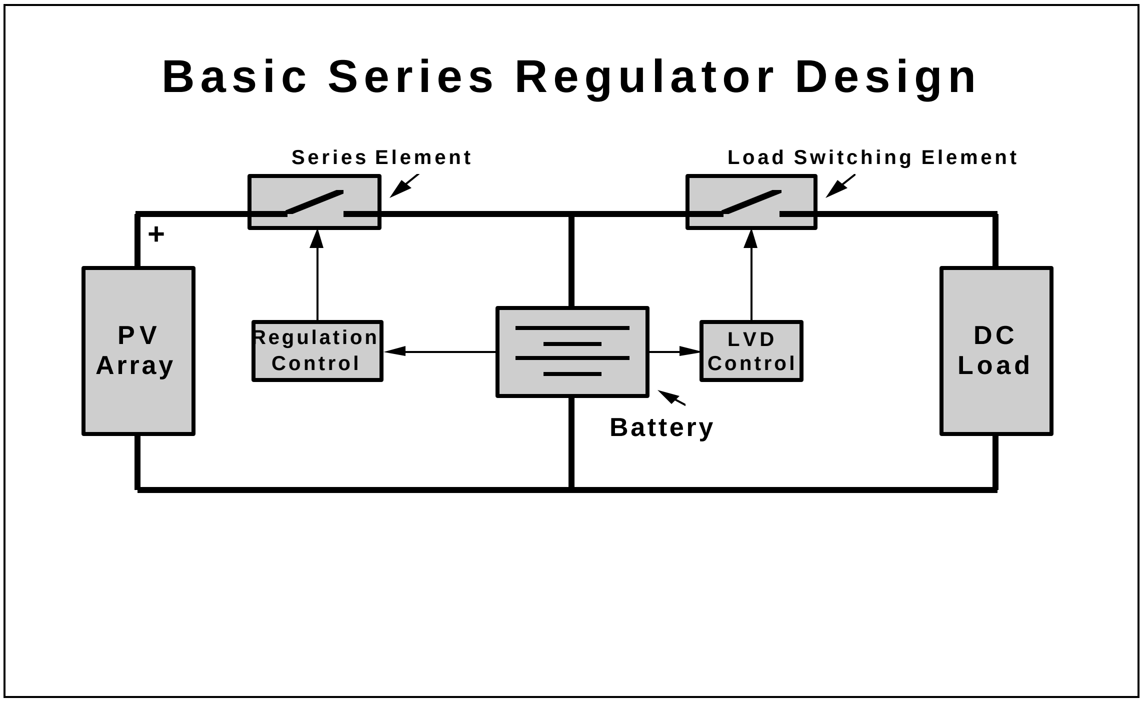


Figure 13. Series controller

Series-Interrupting Design

The most simple series controller is the series-interrupting type, involving a one-step control, turning the array charging current either on or off. The charge controller constantly monitors battery voltage, and disconnects or open-circuits the array in series once the battery reaches the regulation voltage set point. After a pre-set period of time, or when battery voltage drops to the array reconnect voltage set point, the array and battery are reconnected, and the cycle repeats. As the battery becomes more fully charged, the time for the battery voltage to reach the regulation voltage becomes shorter each cycle, so the amount of array current passed through to the battery becomes less each time. In this way, full charge is approached gradually in small steps or pulses, similar in operation to the shunt-interrupting type controller. The principle difference is the series or shunt mode by which the array is regulated.

Similar to the shunt-interrupting type controller, the series-interrupting type designs are best suited for use with flooded batteries rather than the sealed VRLA types due to the way power is applied to the battery.

Series-Interrupting, 2-step, Constant-Current Design

This type of controller is similar to the series-interrupting type, however when the voltage regulation set point is reached, instead of totally interrupting the array current, a limited constant current remains applied to the battery. This ‘trickle charging’ continues either for a pre-set period of time, or until the voltage drops to the array reconnect voltage due to load demand. Then full array current is once again allowed to flow, and the cycle repeats. Full charge is approached in a continuous fashion, instead of smaller steps as described above for the on-off type controllers. Some two-stage controls increase array current immediately as battery voltage is pulled down by a load. Others keep the current at the small trickle charge level until the battery voltage has been pulled down below some intermediate value (usually 12.5-12.8 volts) before they allow full array current to resume.

Series-Interrupting, 2-Step, Dual Set Point Design

This type of controller operates similar to the series-interrupting type, however there are two distinct voltage regulation set points. During the first charge cycle of the day, the controller uses a higher regulation voltage provide some equalization charge to the battery. Once the array is disconnected from the battery at the higher regulation set point, the voltage drops to the array reconnect voltage and the array is again connected to the battery. However, on the second and subsequent cycles of the day, a lower regulation voltage set point is used to limit battery overcharge and gassing.

This type of regulation strategy can be effective at maintaining high battery state of charge while minimizing battery gassing and water loss for flooded lead-acid types. The designer must make sure that the dual regulation set points are properly adjusted for the battery type used. For example, typical set point values (at 25 ^{o}C) for this type of controller used with a flooded lead-antimony battery might be 15.0 to 15.3 volts for the higher regulation voltage, and between 14.2 and 14.4 volts for the lower regulation voltage.

Series-Linear, Constant-Voltage Design

In a series-linear, constant-voltage controller design, the controller maintains the battery voltage at the voltage regulation set point. The series regulation element acts like a variable resistor, controlled by the controller battery voltage sensing circuit of the controller. The series element dissipates the balance of the power that is not used to charge the battery, and generally requires heat sinking. The current is inherently controlled by the series element and the voltage drop across it.

Series-linear, constant-voltage controllers can be used on all types of batteries. Because they apply power to the battery in a controlled manner, they are generally more effective at fully charging batteries than on-off type controllers. These designs, along with PWM types are recommended over on-off type controllers for sealed VRLA type batteries.

Series-Interrupting, Pulse Width Modulated (PWM) Design

This algorithm uses a semiconductor switching element between the array and battery which is switched on/off at a variable frequency with a variable duty cycle to maintain the battery at or very close to the voltage regulation set point. Although a series type PWM design is discussed here, shunt-type PWM designs are also popular and perform battery charging in similar ways. Similar to the series-linear, constant-voltage algorithm in performance, power dissipation within the controller is considerably lower in the series-interrupting PWM design.

By electronically controlling the high speed switching or regulation element, the PWM controller breaks the array current into pulses at some constant frequency, and varies the width and time of the pulses to regulate the amount of charge flowing into the battery as shown in Figure 12-8. When the battery is discharged, the current pulse width is practically fully on all the time. As the battery voltage rises, the pulse width is decreased, effectively reducing the magnitude of the charge current.

The PWM design allows greater control over exactly how a battery approaches full charge and generates less heat. PWM type controllers can be used with all battery type, however the controlled manner in which power is applied to the battery makes them preferential for use with sealed VRLA types batteries over on-off type controls. To limit overcharge and gassing, the voltage regulation set points for PWM and constant-voltage controllers are generally specified lower than those for on-off type controllers. For example, a PWM controller operating with a nominal 12 volt flooded lead-antimony battery might use a VR set point of 14.4 to 14.6 volts at 25 ^{o}C, while an on-off controller used with the same battery might require a VR set point of between 14.7 and 15.0 volts to fully recharge the battery on a typical day.

Daily Operational Profiles for Charge Controllers

The following sections present typical daily operational profiles for a few of the different types of battery charge controllers commonly used in small stand-alone PV systems. These daily profiles show how the different charge controller algorithms regulate the current and voltage from the PV array to protect the battery from overcharge.

About the Charge Controller Daily Profiles

The data presented in the graphs were measured during tests on operational PV lighting systems at the Florida Solar Energy Center (FSEC) in February 1993. Several identical systems were monitored, with the exception that each system used a different battery charge controller. The data presented here are for a selected ‘clear day’ with no cloud cover, clearly showing the charge controller regulation effects.

To properly understand the data presented in the graphs, it is helpful to know how they were measured. The measured parameters included among others the solar irradiance (Sun), battery voltage (Vbat) and current (Ibat), and PV array voltage (Vpv) and current (Ipv). The designations in parenthesis are used in the legend key for the daily profiles. Each parameter was sampled every 10 seconds and averaged over a six minute period and recorded for a total of 240 data points daily. In addition, the minimum and maximum of the battery voltage samples were recorded every six minutes. These minimum and maximum voltages (based on 10 second samples) are key to understanding how a battery charge controller operates.

In each of the following figures showing charge controller daily performance, there are two graphs. The top graph shows the battery and PV array voltage versus time for the ‘clear day’. Note that for clarity, the battery voltage is plotted on the left y-axis, while the PV array voltage is plotted with respect to the right y-axis on a different scale. The bottom graph shows the battery and PV array currents over the day, as well as the solar irradiance. Note that the currents are plotted on the left y-axis, and the irradiance is plotted on the right y-axis.

The sizing of the battery, PV array and load profile in the test systems was configured to typify commercially available PV lighting systems. The different charge controllers were selected from those commonly used in these type and sizes of systems. The following table lists the nominal specifications for the FSEC test systems.

Nominal Specifications for FSEC Test Systems

Design Insolation:	5 kWh/m^2-day
PV Array:	Nominal 100 watt Pmp, 6 amps Imp
Battery:	Flooded Lead Antimony, 12 volt, 100 Ah @ 20 hr rate
Load:	Nominal 3 amps, 8 hours nightly, 24 amp-hours per day

Controller:	Variable

A final word of caution when examining the following daily operational profiles for the different charge controllers. Since these were test systems designed to investigate not only the behavior of the different controllers, but the effects the regulation set points had on maintaining battery state of charge, the set points were not always optimized for the specific system design. In some cases this was intentional, while in other cases was the result of the controller operating characteristics. The main point to emphasize however is that the daily profiles presented here show how the charge controllers typically operate in PV systems.

Daily Profile for Shunt-Interrupting Charge Controller

A 24-hour daily profile for a small stand-alone PV lighting system operating with a shunt-interrupting (on-off) type battery charge controller is shown in Figure 14. Beginning at the left of the two graphs (midnight), the load is operating and battery voltage decreases steadily from about 12.1 volts to 11.9 volts while being discharged at about 3 amps. At about 0400 hours, the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.35 volts. At sunrise (about 0700 hours), the battery voltage begins to increase as the PV array current is fed into the battery. Until about noon time (1200 hours), the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged. Note that during this period, the battery charge controller is not regulating and nearly all the PV array current is fed into the battery.

At approximately noon (1200 hours), the battery voltage reaches the regulation voltage set point for the battery charge controller, and the controller begins to regulate the PV array current. When this occurs, the battery current decreases in a jagged manner characteristic of the *interrupting (on-off)* algorithm. The *shunt* characteristic is demonstrated by the fact that once regulation begins, the PV array current continues to follow the same profile as the solar irradiance, while the six-minute average PV array voltage decreases to an average of about 5 volts. In effect this controller shunts, or ‘short-circuits’ the PV array at regulation, causing the PV voltage to reduce and forcing the current to the array short-circuit current point.

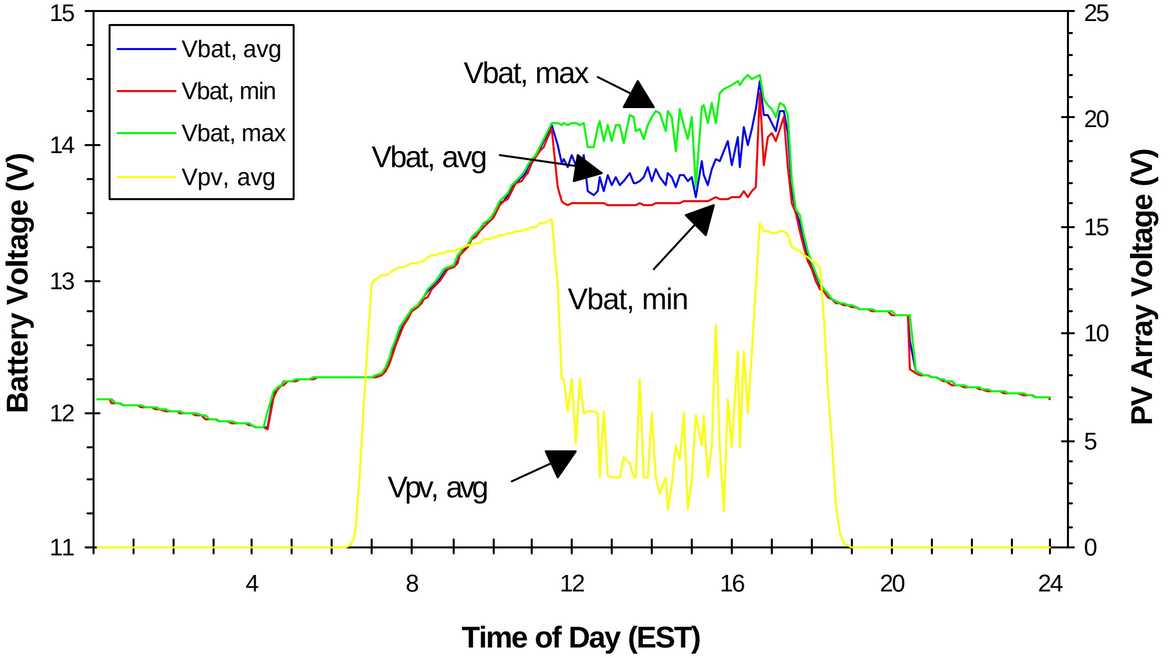
Up until regulation, the minimum and maximum battery voltages closely match the six minute average battery voltage throughout the morning and during load operation. With the onset of regulation, the minimum and maximum battery voltages are different from the six-minute averaged voltages, and indicate the approximate controller set points. During regulation, the maximum battery voltage is between 14.3 and 14.5 volts. This maximum battery voltage corresponds to the voltage regulation set point for the battery charge controller. The minimum battery voltage is consistently about 13.7 volts, corresponding to the voltage at which the charge controller reconnects the array to the battery to resume charging. The fact that the minimum voltage is consistent over the regulation period indicates that the controller is regulating or ‘cycling’ the battery voltage between the voltage regulation and array reconnect set points at least once every six minutes. The differences in the minimum and maximum battery voltages during regulation demonstrate the operation of an interrupting or on-off type controller algorithm. This voltage difference is often referred to as the controller’s hysteresis, or array regulation voltage span. The hysteresis is an important specification for on-off controllers, and must be selected properly to achieve good array energy utilization and proper battery recharging.

Towards the end of the sunlight hours (1600-1700 hours), the PV array current output reduces to a low enough value, in this case about 2.5 amps, wherein regulation is not required to limit the battery voltage below the regulation set point of the controller. Once the sun sets (about 1800 hours), the battery voltage begins a gradual decrease to it’s open-circuit voltage. Notice how the open-circuit voltage at this time is higher than in the morning before the battery was recharged, indicating a higher state of charge. At about

2030 hours, the 3 amp load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.

Shunt-Interrupting Charge Controller

Clear Day Operational Profile in PV Lighting System



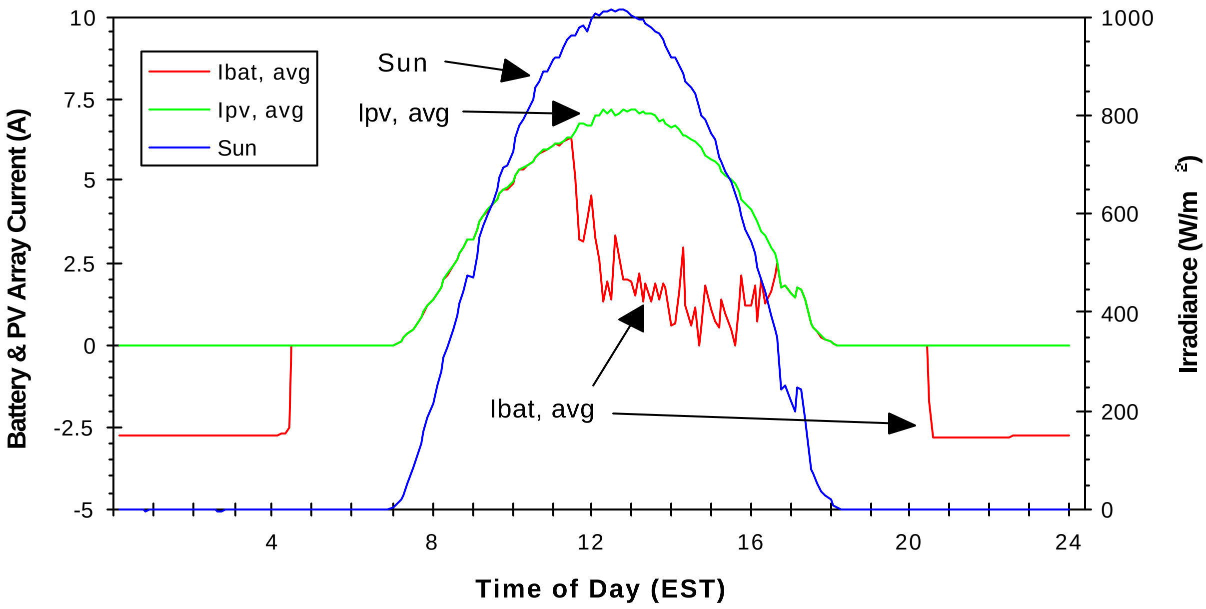


Figure 14

Daily Profile for Series-Interrupting Charge Controller

A 24-hour daily profile for a small stand-alone PV lighting system operating with a series-interrupting (on-off) type battery charge controller is shown in Figure 15. Beginning at the left on the two graphs (midnight), the load is operating and battery voltage decreases steadily from about 11.9 volts to 11.7 volts while being discharged at about 3 amps. At about 0400 hours, the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.1 volts. At sunrise (about 0700 hours), the battery voltage begins to increase as the PV array current begins to recharge the battery. Until about noon time (1200 hours), the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged. Note that during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current. However, the minimum battery voltage shows values slightly lower than the average and maximum battery voltages during the morning charging period. This is a particular characteristic of the charge controller in this test system, by which the array is periodically disconnected from the battery to sense night time conditions.

At about noon (1200 hours), the battery voltage reaches the regulation voltage of the battery charge controller (about 14.1 volts), and the controller begins to regulate the PV array current. When this occurs, the battery current decreases to the jagged characteristic of the *interrupting (on-off)* algorithm. The *series* characteristic can be seen by the fact that once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the array open-circuit voltage. In effect this controller open-circuits the array in a series manner during regulation, resulting in zero PV current and operating the array at the open-circuit voltage point.

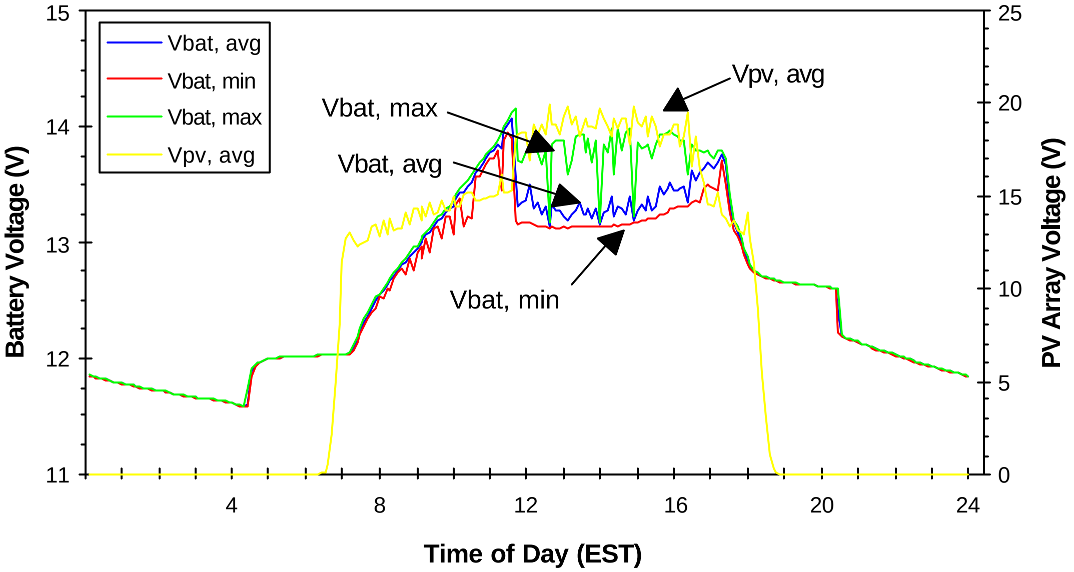
With the onset of regulation, the minimum and maximum battery voltages are distinguished from the six-minute average voltage, and show the approximate controller set points. After regulation, the maximum battery voltage is about 14.1 volts. This maximum battery voltage corresponds to the voltage regulation set point for the battery charge controller. The minimum battery voltage is between 13.2 and 13.4 volts, corresponding to the voltage at which the charge controller reconnects the array to the battery to resume charging.

Once the sun sets (about 1800 hours), the battery voltage begins a gradual decrease to it’s open-circuit voltage. Note how the open circuit -voltage at this time is higher than in the morning before the battery was recharged. At about 2030 hours, the 3 amp load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.

In comparison with the shunt-interrupting controller discussed previously, the regulation set point for this series-interrupting controller was considerably lower, resulting in a lower battery state of charge. This is indicated by the lower battery voltage just prior to the load being disconnected in the early morning.

Series-Interrupting Charge Controller

Clear Day Profile in PV Lighting System



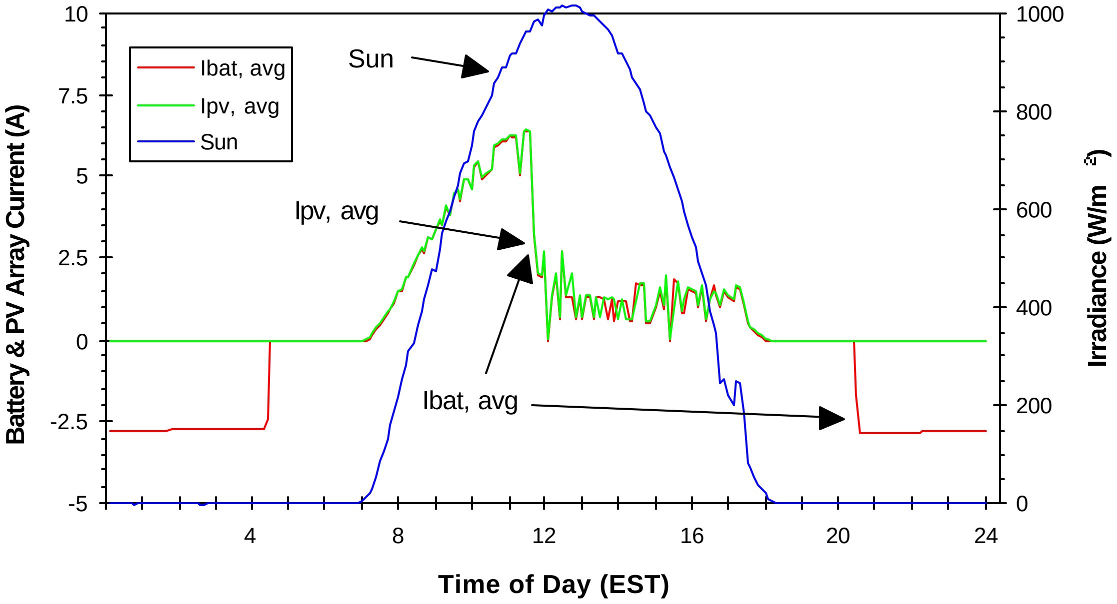


Figure 15

Daily Profile for Modified Series Charge Controller

A 24-hour daily profile for a small stand-alone PV lighting system operating with a modified series type battery charge controller is shown in Figure 16. Beginning at the left of the two graphs (midnight), the load is operating and battery voltage decreases steadily from about 12.25 volts to 12 volts while being discharged at about 3 amps. At about 0430 hours, the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.4 volts. At sunrise (about 0700 hours), the battery voltage begins to increase as the PV array current recharges the battery. Until about noon time (1200 hours), the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged. Note that during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current.

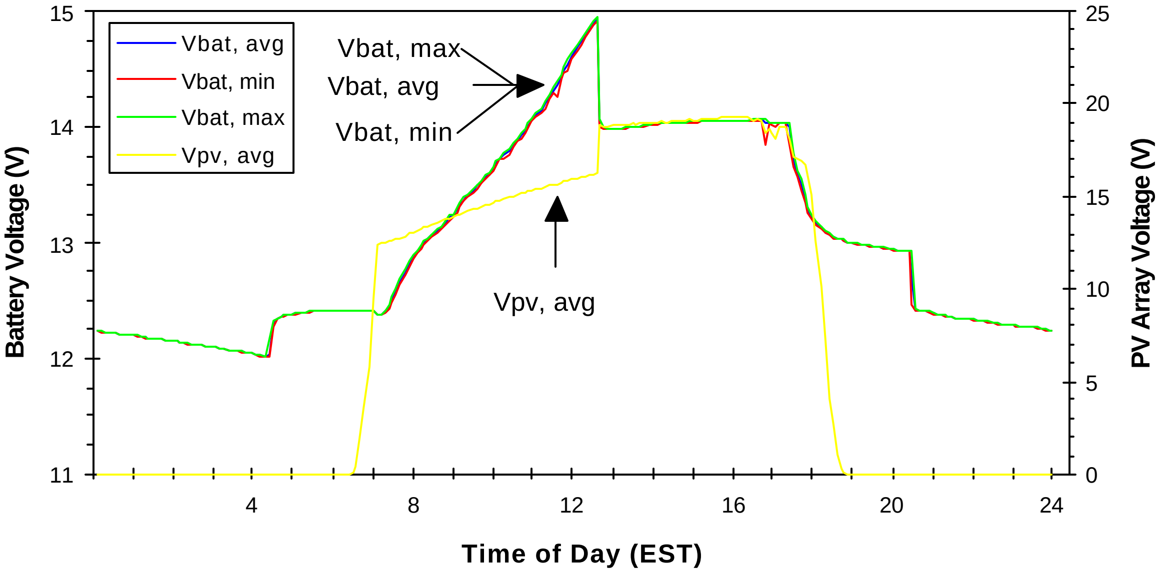
At about noon (1200 hours), the battery voltage reaches the regulation voltage set point for the battery charge controller (about 14.9 volts), and the controller begins to regulate the PV array current. In contrast to the series- and shunt-interrupting controllers discussed previously, the battery current is not entirely disconnected from the battery, but only limited to a lower value. When this occurs, the battery current decreases to below 2 amps, and remains in a current-limited mode through the remainder of the day. The *series* characteristic is shown by the fact that once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the open-circuit array voltage. In principle, this controller regulates the array in a series-linear manner, by increasing the resistance between the PV array and battery. The resistance is held at such a value that a limited amount of current is allowed to flow from the PV array to battery after initial regulation.

With the onset of regulation, the minimum and maximum battery voltages are indistinguishable from the six-minute average voltage, indicating that the controller in not an on-off interrupting type design. After the initial battery regulation at 14.9 volts, the voltage after regulation remains at about 14.1 volts through the remainder of the day.

Once the sun sets (about 1800 hours), the battery voltage begins a gradual decrease to it’s open-circuit voltage. At about 2030 hours, the 3 amp load is again reconnected and the battery voltage begins to steadily decrease as the battery is discharged.

Modified Series Charge Controller

Clear Day Profile in PV Lighting System



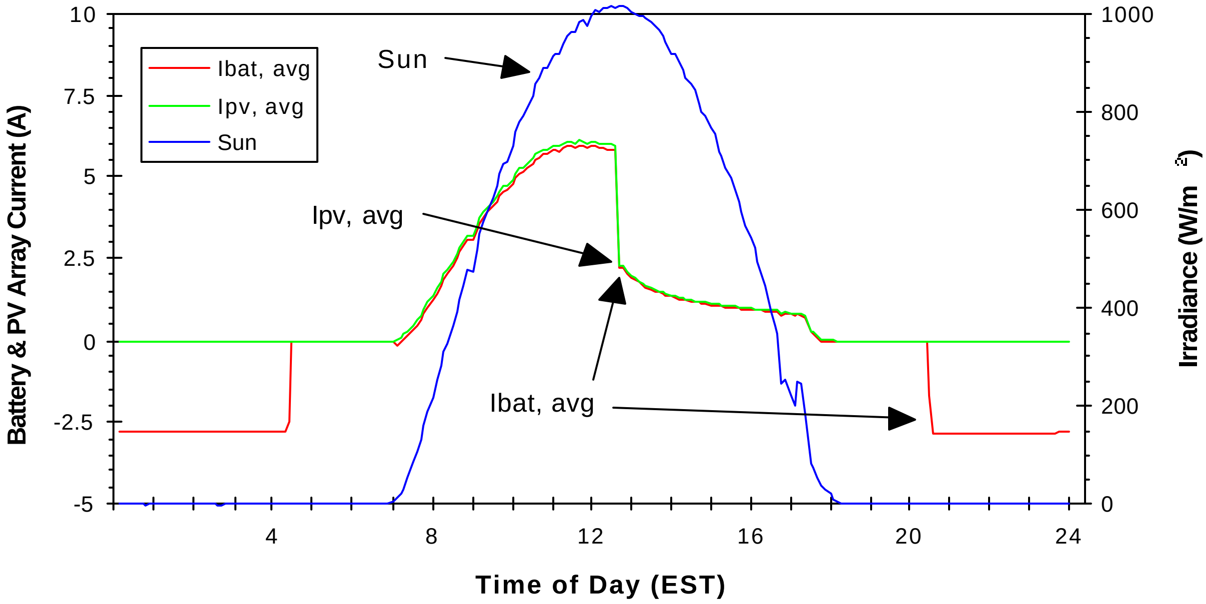


Figure 16

Daily Profile for Constant-Voltage Series Charge Controller

A 24-hour daily profile for a small stand-alone PV lighting system operating with a constant-voltage series type battery charge controller is shown in Figure 17. Beginning at the left on the two graphs (midnight), the load is operating and battery voltage decreases steadily from about 12.1 volts to 11.9 volts while being discharged at about 3 amps. At about 0430 hours, the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.3 volts. At sunrise (about 0700 hours), the battery voltage begins to increase as the PV array current charges the battery. Until about noon time (1200 hours), the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged. Note that during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current.

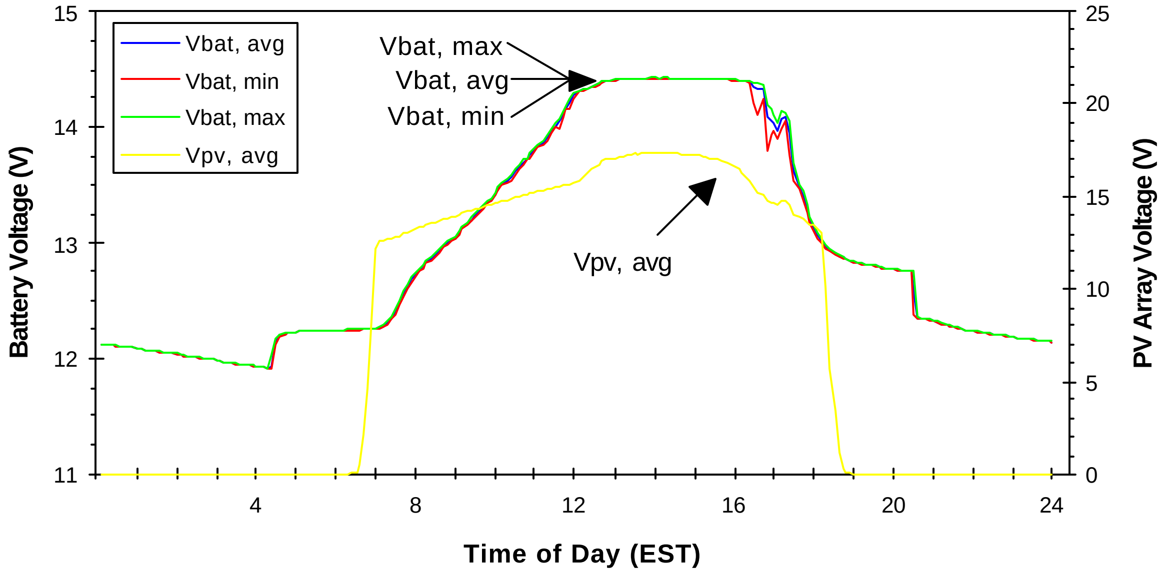
At about noon (1200 hours), the battery voltage reaches the regulation voltage set point for the battery charge controller (about 14.5 volts), and the controller begins to regulate the PV array current.   When this occurs, the battery current gradually decreases to about 1 amp by the end of the day. The *series* characteristic of this controller is shown by the fact that once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the open-circuit array voltage.   In principle, this controller regulates the array in a series-linear manner, by increasing the resistance between the PV array and battery through semiconductor devices such as MOSFETs. The resistance is held at such a value that limits amount of current that is allowed to flow from the PV array to battery after initial regulation, while holding the array voltage at a constant value corresponding to he controller’s regulation voltage.

With the onset of regulation, the minimum and maximum battery voltages are indistinguishable from the six-minute average voltage, indicating that the controller in not an on-off interrupting type design. After the initial regulation at 14.5 volts, the voltage after regulation remains at this level through the remainder of the day.

Moving toward sunset (about 1800 hours), the array current is no longer high enough to maintain the battery at the regulation voltage, and the battery voltage begins a gradual decrease to it’s open-circuit voltage. At about 2030 hours, the 3 amp load is again reconnected and the battery voltage begins to steadily decrease until the next day when charging resumes.

Constant-Voltage Series Charge Controller

Clear Day Profile in PV Lighting System



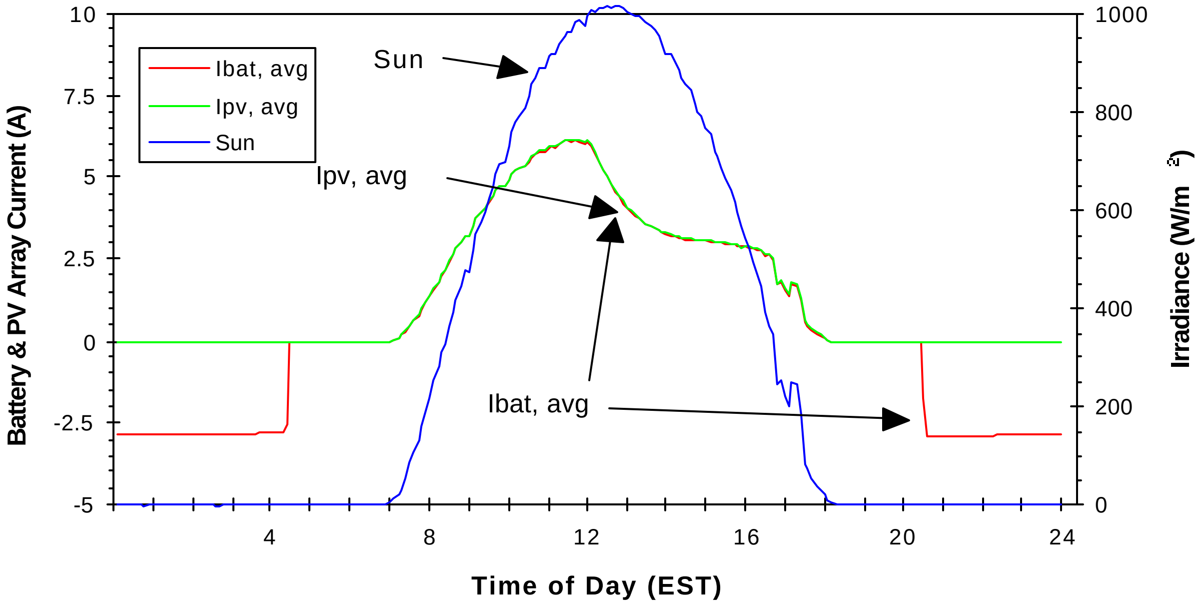


Figure 17

Daily Profile for Pulse-Width-Modulated Series Charge Controller

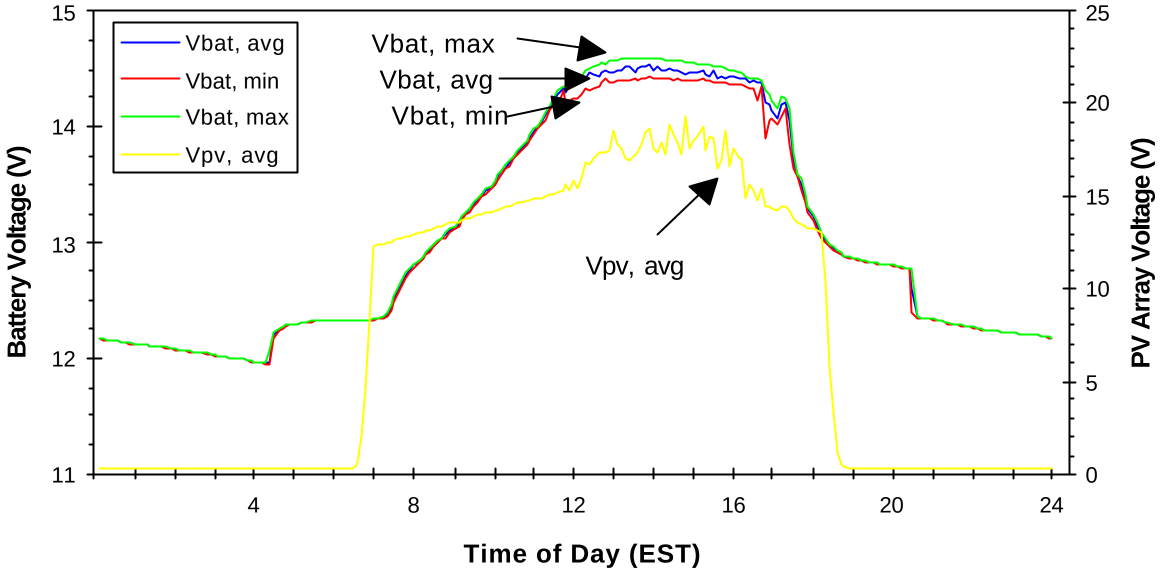
A 24-hour daily profile for a small stand-alone PV lighting system operating with a pulse-width-modulated (PWM) series type battery charge controller is shown in Figure 18. Beginning at the left of the two graphs (midnight), the load is operating and battery voltage decreases steadily from about 12.2 volts to 11.9 volts while being discharged at about 3 amps. At about 0430 hours, the load current is disconnected by the charge controller load regulation/timing circuit. At this point the battery current goes to zero, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.3 volts. At sunrise (about 0700 hours), the battery voltage begins to increase as the PV array current charges the battery. Until about noon time (1200 hours), the PV array current and the battery voltage increase steadily with increasing insolation as the battery is being recharged. Note that during this period, the battery charge controller is not regulating and the PV array current is approximately the same as the battery current.

At about noon (1200 hours), the battery voltage reaches the regulation voltage set point for the battery charge controller (about 14.5 volts), and the controller begins to regulate the PV array current. When this occurs, the battery current decreases in a jagged manner, and remains in a current-limited mode through the remainder of the day. The *series* characteristic can be seen by the fact that once regulation begins, the average PV array current also decreases, while the average PV array voltage approaches the open-circuit array voltage. In principle, this controller regulates the array in a series manner, by decreasing the width or time of the current pulses supplied to the battery. In the PWM design, an oscillating signal operating at a frequency of several hundred Hertz is used to regulate the array current. When the controller is not regulating, the full array current is applied to the battery. When the regulation voltage is reached, the current pulses are gradually reduced to hold the battery voltage at the regulation set point. In effect, the PWM design operates similar to the constant-voltage controller, with the exception that there is a small hysteresis between the minimum and maximum battery voltage after regulation. The PWM is essentially a high switching speed on-off type or interrupting type controller which does not allow the battery voltage to drop significantly during regulation.

Once the sun sets (about 1800 hours), the battery voltage begins a gradual decrease to it’s open-circuit voltage. At about 2030 hours, the 3 amp load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.

Pulse-Width-Modulated Series Charge Controller

Clear Day Profile in PV Lighting System



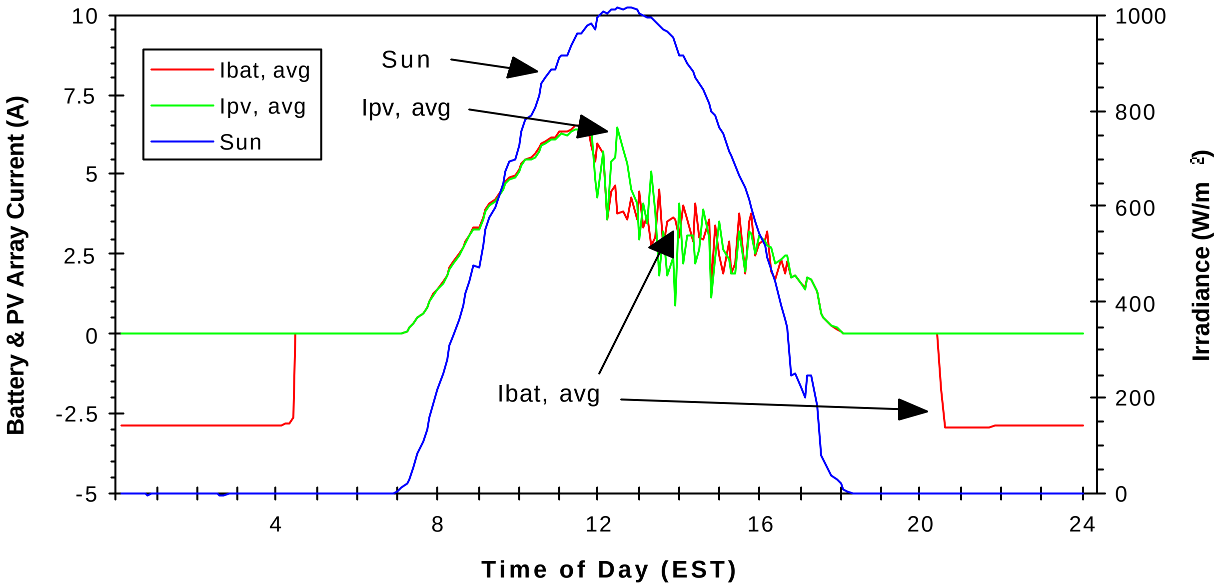


Figure 18

Voltage Regulation Set Point Selection

As discussed earlier, it is critical that the voltage regulation set point of a charge controller be properly selected to achieve optimal battery performance and lifetime in PV systems. The set points are probably more important than the particular type of controller design. If a very sophisticated charge controller design is used, but it is adjusted to an improper charge regulation voltage, no benefit will result from the sophistication and added expense, and battery performance is likely to suffer. A relatively simple design with the set points adjusted properly will work better than a sophisticated controller which is not set properly for the application.

The optimal selection of the voltage regulation set point will ensure that the battery is maintained at the highest possible state of charge without overcharging. The specific set point values to use for a particular battery type, controller design and application depend on a number of factors. While there are no simple methods to arrive at the optimal set points, some general guidelines for voltage regulation set point selection are discussed next.

In stand-alone PV systems, the ways in which a battery is charged are generally much different from the charging methods battery manufacturers recommend. A battery in a PV system must be fully recharged during the few daylight hours, much shorter time periods than the manufacturers use. For this reason, the voltage regulation set point must be set high enough to permit high utilization of the array current, but not to high as to excessively overcharge the battery. Therefore, how to determine when a battery is being overcharged is the key issue limiting the voltage regulation set point used in PV system charge controllers.

Suggestions for Voltage Regulation Set Point Selection

Some recommended ranges for charge regulation voltages at 25 °C for different battery types used in PV systems are presented in the Table 5 below. These values are typical of voltage regulation set points for battery charge controllers used in small PV systems. These recommendations are meant to be only general in nature, and specific battery manufacturers should be consulted for their suggested values.

Table 5. Voltage Regulation Set Point Selection

		Battery Type			
Controller Design Type	**Charge Regulation Voltage at 25 °C**	Flooded Lead-Antimony	Flooded Lead-Calcium	Sealed, Valve Regulated Lead-Acid	Flooded Pocket Plate Nickel-Cadmium
On-Off, Interrupting	Per nominal 12 volt battery	14.6 - 14.8	14.2 - 14.4	14.2 - 14.4	14.5 - 15.0
	Per Cell	2.44 - 2.47	2.37 - 2.40	2.37 - 2.40	1.45 - 1.50
Constant-Voltage, PWM, Linear	Per nominal 12 volt battery	14.4 - 14.6	14.0 - 14.2	14.0 - 14.2	14.5 - 15.0
	Per Cell	2.40 - 2.44	2.33 - 2.37	2.33 - 2.37	1.45 - 1.50

The charge regulation voltage ranges presented in Table 12-1 are much higher than the typical charge regulation values often presented in manufacturer's literature. This is because battery manufacturers often speak of regulation voltage in terms of the *float voltage*, or the voltage limit suggested for when batteries are *float charged* for extended periods (for example, in uninterruptible power supply (UPS) systems). In these and many other commercial battery applications, batteries can be "trickle" or float charged for extended period, requiring a voltage low enough to limit gassing. Typical float voltages are between 13.5 and 13.8 volts for a nominal 12 volt battery, or between 2.25 and 2.30 volts for a single cell.

In a PV system however, the battery must be recharged within a limited time (usually during sunlight hours), requiring that the regulation voltage be much higher than the manufacturer's float voltage to ensure that the battery is fully recharged. If charge regulation voltages in a typical PV system were set at the manufacturer's recommended float voltage, the batteries would never be fully charged.

Temperature Compensation

As discussed previously, the electrochemical reaction and gassing in a battery is highly dependent on temperature. Lower battery temperature slow down the reaction, reduce capacity and increase the voltage required for gassing. Conversely, higher temperatures accelerate the reaction, increase grid corrosion, and lower the gassing voltage. For these reasons, temperature compensation (TC) of the VR set point is often used in PV systems.

Where environmental conditions cause battery temperatures to vary more than ±5 ^{o}C from the rated conditions, compensation of the charge regulation set point is highly recommended. Temperature compensation is also strongly recommended for all type of sealed VRLA captive electrolyte batteries, which are sensitive to overcharge. By using TC, a battery can be fully charged during cold weather, and protected from overcharge during hot weather.

Charge controllers measure or approximate the battery temperature to perform temperature compensation. Battery temperatures may be sensed with an external probe connected to the controller, or approximated with an on-board sensor in controller circuitry. If battery temperatures are lower than the design condition, the regulation voltage is increased to allow the battery to reach a moderate gassing level and fully recharge. Conversely, the regulation set point is reduced if battery temperatures are greater than design conditions. A widely accepted value of temperature compensation for lead-acid batteries is -5 mV/^{o}C /cell. For a nominal 12 volt battery, this amounts to 30 mV per ^{o}C. Where battery temperatures vary by as much as 30 ^{o}C, temperature compensation may result in the regulation set point varying by as much as 1.0 volt in a 12 volt system. It is important to notice that the TC coefficient is negative, meaning that increases in temperature require a reduction in the charge regulation voltage.

If the electrolyte concentration has been adjusted for local ambient temperature (increase in specific gravity for cold environments, decrease in specific gravity for warm environments) and temperature variation of the batteries is minimal, compensation may not be as critical. Typically, the LVD set point is not temperature compensated unless the batteries operate below 0 ^{o}C on a frequent basis.

Charge Controller Selection

The selection and sizing of charge controllers and system controls in PV systems involves the consideration of several factors, depending on the complexity and control options required. While the primary function is to prevent battery overcharge, many other functions may also be used, including low voltage load disconnect, load regulation and control, control of backup energy sources, diversion of energy to and auxiliary load, and system monitoring. The designer must decide which options are needed to satisfy the requirements of a specific application. The following list some of the basic considerations for selecting charge controllers for PV systems.

- System voltage
- PV array and load currents
- Battery type and size
- Regulation algorithm and switching element design
- Regulation and load disconnect set points
- Environmental operating conditions
- Mechanical design and packaging
- System indicators, alarms, and meters
- Overcurrent, disconnects and surge protection devices
- Costs, warranty and availability

Sizing Charge Controllers

Charge controllers should be sized according to the voltages and currents expected during operation of the PV system. The controller must not only be able to handle typical or rated voltages and currents, but must also be sized to handle expected peak or surge conditions from the PV array or required by the electrical loads that may be connected to the controller. It is extremely important that the controller be adequately sized for the intended application. If an undersized controller is used and fails during operation, the costs of service and replacement will be higher than what would have been spent on a controller that was initially oversized for the application.

Typically, we would expect that a PV module or array produces no more than it's rated maximum power current at 1000 W/m^2 irradiance and 25 ^{o}C module temperature. However, due to possible reflections from clouds, water or snow, the sunlight levels on the array may be "enhanced" up to 1.4 times the nominal 1000 W/m^2 value used to rate PV module performance. The result is that peak array current could be 1.4 times the nominal peak rated value if reflection conditions exist. For this reason, the peak array current ratings for charge controllers should be sized for about 140% or the nominal peak maximum power current ratings for the modules or array.

The size of a controller is determined by multiplying the peak rated current from an array times this "enhancement" safety factor. The total current from an array is given by the number of modules or strings in parallel, multiplied by the module current. To be conservative, use the short-circuit current (Isc) is generally used instead of the maximum power current (Imp). In this way, shunt type controllers that operate the array at short-circuit current conditions are covered safely.

Operating Without a Charge Controller

In most cases a charge controller is an essential requirement in stand-alone PV systems. However there are special circumstances where a charge controller may not be needed in small systems with well defined loads. Beacons and aids to navigation are a popular PV application which operate without charge regulation. By eliminating the need for the sensitive electronic charge controller, the design is simplified, at lower cost and with improved reliability.

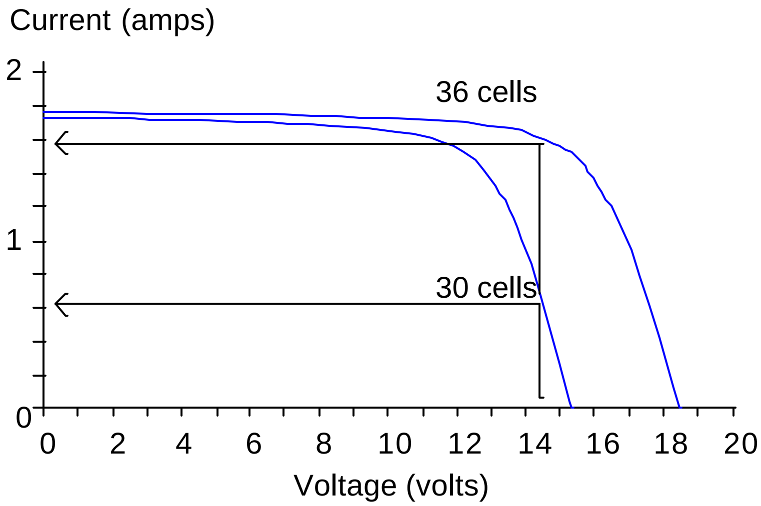
The system design requirements and conditions for operating without a charge controller must be well understood because the system is operating without any overcharge and overdischarge protection for the batteries. There are two cases where battery charge regulation may not be required: (1) when a low voltage "self-regulating module" is used in the proper climate; and (2) when the battery is very large compared to the array. Each of these cases are discussed next.

Using Low-Voltage "Self-Regulating" Modules

The use of "low-voltage" or "self-regulating" PV modules is one approach used to operate without battery charge regulation. This does not mean that the modules have an electronic charge controller built-in, but rather it refers to the low voltage design of the PV modules. When a low voltage module, battery and load are properly configured, the design is called a "self-regulating system".

Typical silicon power modules used to charge nominal 12 volt batteries usually have 36 solar cells connected in series to produce and open-circuit voltage of greater than 21 volts and a maximum power voltage of about 17 volts. Why do we generally use modules with a maximum power voltage of 17 volts when we are only charging a 12 volt battery to maybe 14.5 volts? Because voltage drops in wiring, disconnects, overcurrent devices and controls, as well as higher array operating temperatures tend to reduce the array voltage measured at the battery terminals in most systems. By using a standard 36 cell PV module we are assured of operating to the left of the "knee" on the array I-V curve, allowing the array to deliver it's rated maximum power current. Even when the array is operating at high temperature, the maximum power voltage is still high enough to charge the battery. If the array were operated to the right of the I-V curve "knee", the peak array current would be reduced, possibly resulting in the system not being able to meet the load demands.

Self-Regulation Using Low-Voltage Module



- **Figure 19**

In the case of using "self-regulating" modules without battery charge regulation, the designer wants to take advantage of the fact that the array current falls off sharply as the voltage increases above the maximum power point. In a "self-regulating" low voltage PV module, there are generally only 28-30 silicon cells connected in series, resulting in an open-circuit voltage of about 18 volts and a maximum power voltage of about 15 volts at 25 ^oC. Under typical operating temperatures, the "knee" of the IV curve falls within the range of typical battery voltages. As a battery becomes charged during a typical day, its voltage rises and results in the array operating voltage increasing towards the maximum power point or "knee" of the IV curve. In addition, the module temperature increases, resulting in a reduction of the maximum power voltage. At some point, the battery voltage high enough that the operating point on the IV curve is to the right of the "knee". In this region of the IV curve, the current reduces sharply with any further increases in voltage, effectively reducing the charge current and overcharge to the battery.

Figure 19 shows a comparison of operating points between a 36-cell and 30-cell PV module. As the battery voltage rises, there is a more dramatic reduction in current from the 30-cell module. In the afternoon, in this example, the battery voltage has risen to about 14.4 volts, and the current from the 30-cell module is almost one third that from the 36-cell module.

Using a "self-regulating module" does not automatically assure that a photovoltaic power system will be a self-regulating system. For self-regulation and no battery overcharge to occur, the following three conditions must be met:

1. ***The load must be used daily.*** If not, then the module will continue to overcharge a fully charged battery. Every day the battery will receive excessive charge, even if the module is forced to operate beyond the "knee" at current levels lower than its Imp. If the load is used daily, then the amp-hours produced by the module are removed from the battery, and this energy can be safely replaced the next day without overcharging the battery. So for a system to be "self-regulating", the load must be consistent and predictable. This eliminates applications where only occasional load use occurs, such

as vacation cabins or RV’s that are left unused for weeks or months. In these cases, a charge controller should be included in the system to protect the battery.

2. ***The climate cannot be too cold.*** If the module stays very cool, the "knee" of the IV curve will not move down in voltage enough, and the expected drop off in current will not occur, even if the battery voltage rises as expected. Often "self-regulating modules" are used in arctic climates for lighting for remote cabins for example, because they are the smallest and therefore least expensive of the power modules, but they are combined with a charge controller or voltage dropping diodes to prevent battery overcharge.

3. ***The climate cannot be too warm.*** If the module heats up too much, then the drop off in current will be too extreme, and the battery may never be properly recharged. The battery will sulfate, and the loads will not be able to operate.

A “self-regulating system” design can greatly simplify the design by eliminating the need for a charge controller, however these type of designs are only appropriate for certain applications and conditions. In most common stand-alone PV system designs, a battery charge controller is required.

Using a Large Battery or Small Array

A charge controller may not be needed if the charge rates delivered by the array to the battery are small enough to prevent the battery voltage from exceeding the gassing voltage limit when the battery is fully charged and the full array current is applied. In certain applications, a long autonomy period may be used, resulting in a large amount of battery storage capacity. In these cases, the charge rates from the array may be very low, and can be accepted by the battery at any time without overcharging. These situations are common in critical application requiring large battery storage, such as telecommunications repeaters in alpine conditions or remote navigational aides. It might also be the case when a very small load and array are combined with a large battery, as in remote telemetry systems.

In general a charging rate of C/100 or less is considered low enough to be tolerated for long periods even when the battery is fully charged. This means that even during the peak of the day, the array is charging the battery bank at the 100 hour rate or slower, equivalent to the typical trickle charge rate that a controller would produce anyway.

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