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Recommended Practices for Charge Controllers

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Task III:

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Recommended Practices for Charge Controllers

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FOREWORD

These Recommended Practices have been prepared for the International Energy Agency's (IEA) Photovoltaic Power Systems Programme (PVPS), Task III. The IEA is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) established in November 1974 to carry out a programme of energy cooperation among its member countries. Task III of the PVPS is concerned with the use of photovoltaic systems and technologies in remote stand-alone and island power applications. It includes government, academic and industrial representatives from fifteen countries.

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Michael Ross

INTRODUCTION

In stand-alone photovoltaic (PV) systems, charge controllers regulate the current from the PV array in order to protect the battery from being overcharged. In addition, most controllers regulate the current to the load, thereby protecting the battery from deep discharges. The charge controller is therefore the energy manager in a stand-alone PV system, ensuring that the battery is cycled under conditions which do not reduce its ability to deliver its rated capacity over its expected lifetime.

Most controllers will initially allow all the current output from the PV array to pass to the battery, then, as the charging nears completion, will taper or interrupt the current according to the battery's ability to accept charge. In addition, some controllers will at regular intervals intentionally overcharge the battery, which mixes the electrolyte and ensures that all the cells within the battery are "equalized" at a full state-of-charge.

Although the controller is one of the least costly components in a stand-alone PV system, it strongly influences the long-term reliability and maintenance costs of a PV system. Choosing the best controller for a particular system and application, and configuring it correctly, are paramount. These Recommended Practices are intended to provide PV system users, operators, and integrators with the most current information on how to choose, configure and maintain controllers in stand-alone PV systems. In addition, it includes sections helpful to manufacturers of charge controllers.

It should be noted that these Recommended Practices apply only to controllers of lead-acid batteries, and should not be used with systems employing nickel-cadmium or other battery technologies. This is not a serious restriction, since the vast majority of PV systems use lead-acid batteries.

This document first gives a general introduction to charge controller terminology and configurations, then discusses issues of controller selection and setpoint determination, and finally provides suggested practices for procurement, installation, and maintenance. Section 1 introduces the few basic concepts underlying charge control for lead-acid batteries, and defines the terms used in subsequent sections. Section 2 deals in more depth with the how charge controllers should function in order to achieve full charging of the batteries under various conditions. Section 3 examines how best to terminate discharge, such that the battery is not discharged to dangerously low levels. Section 4 overviews features that have been found useful on many charge controllers. Section 5 is aimed at purchasers of charge controllers, and should help them decide which controller best meets their needs. Section 6 is a brief introduction to methods for charging batteries in systems containing both PV arrays and other electrical generators. It focusses on the questions of when a genset should be started and how long it should run. Installation and maintenance procedures are described in Section 7; a trouble-shooting chart constitutes Section 8, and Section 9 lists the testing a charge controller should undergo in order to verify that it will function satisfactorily. The document finishes with a glossary, a bibliography, and a list of the mailing addresses of many manufacturers of charge controllers.

The field of charge control, while seemingly quite straightforward, has turned out to be one of the most problematic issues in photovoltaic system operation. These Recommended Practices are gleaned from a variety of sources representing current understanding of how best to treat lead-acid batteries in photovoltaic systems. A careful reading of these sources, however, reveals that a consensus does not exist on many matters related to charge control. It is clear that these Recommended Practices will require modification and refinement as understanding of the field changes. Therefore, the reader should be cautioned that this report is a good primer on charge control, but can not be considered definitive.

1 BACKGROUND AND TERMINOLOGY

When a lead-acid battery is charged, its voltage rises. When the charge current is first turned on, the internal resistance of the battery resists the current, and the voltage immediately rises above the open circuit voltage. After this initial jump, the voltage continues to rise, but more gradually, as the battery becomes charged.

Towards the end of charge, the voltage rises sharply as the battery begins to “gas”. “**Gassing**” is the decomposition of the liquid water into hydrogen and oxygen gases, and is also called “electrolysis”. If gassing is left to continue for a long period of time, the battery is “**overcharged**”, resulting in accelerated corrosion of the battery plates, loss of electrolyte, and physical damage to the plates. Overcharging should be limited, therefore.

Some gassing is necessary, however. When a battery reaches the voltage at which gassing begins, it is not yet fully charged. In order to complete the charge, the battery must gas for a short period of time, during which a portion of the charge current continues to charge the battery while the remainder causes gassing. In batteries “**flooded**” with electrolyte (as opposed to those in which the electrolyte is immobilized in a **gel** or in an **absorbent glass mat (AGM)**), the gassing stirs the electrolyte, ensuring that it is at the same level of acidity everywhere. If this final step of charging is not permitted, the battery will age prematurely due to corrosion caused by **stratification**, the accumulation of highly acidic electrolyte at the bottom of the battery, and to **sulfation**, the conversion of useful battery plate material into hard crystals that do not participate in the reaction.

When a lead-acid battery is discharged, its voltage drops. Discharging can not continue indefinitely: eventually there is no more battery material to react, and the battery is damaged. Thus, **overdischarge** should be avoided.

A charge controller is an electronic circuit which monitors the charge in and out of the battery and, based on a set of voltage thresholds (termed setpoints), regulates current flow in order to limit overcharge and overdischarge. Two basic methods, called “**interrupting**” charging and “**constant voltage**” (CV) charging, are used. Interrupting charging is also known as “on/off” charging and constant voltage charging is also known as “**constant potential**” charging. There exists a large number of variations of these basic methods, as well.

In on/off charging, the controller acts as a switch. During charging, the controller will permit all of the current from the PV array to flow to the battery. When the voltage rises to an upper threshold, called the “**voltage regulation**” (VR) or “**charge termination**” setpoint, the charge current is turned off. With time, the battery voltage will drift downwards; when it hits a “**voltage regulation reconnect**” (VRR) or “**charge resumption**” setpoint, slightly below the VR setpoint, the charge current will be turned back on. In this way, the battery cycles between the VR and the VRR setpoint. At first, the cycling will occur slowly, but as the battery approaches full charge, the cycling will increase in frequency. To circumvent this, some controllers do not use a VRR setpoint, but rather wait a certain period of time following disconnection at the VR setpoint before reconnecting the array.

The lower the VRR voltage, the longer the array current will be interrupted from charging the battery; on the other hand, if the VRR is too close to the VR setpoint, then the control element will oscillate, inducing noise and possibly harming the switching element. These setpoints are shown conceptually as part of a typical charge/discharge cycle in **Figure 1**.

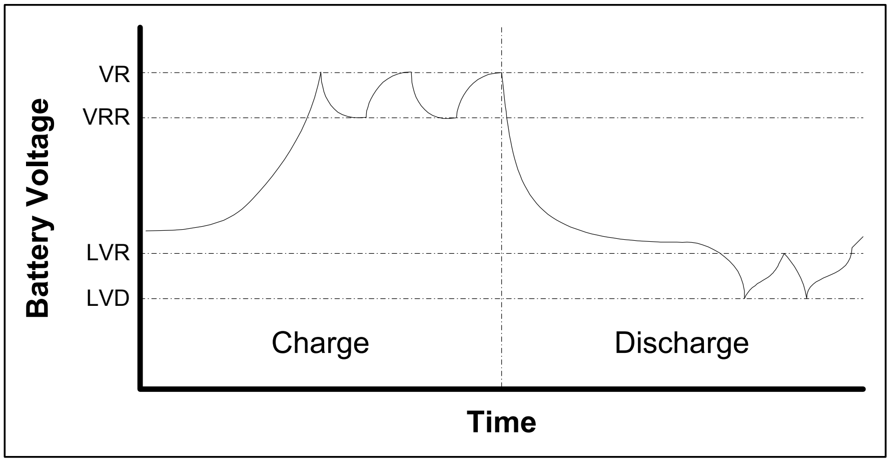

Figure 1: Charge and Discharge for On/Off Charging

On/Off controllers often have difficulty fully charging batteries when the battery bank is fairly small compared with the size of the photovoltaic array, a situation that tends to arise in systems with low levels of autonomy. This results from the relatively high charge currents that occur during sunny days. The internal resistance of the battery causes higher currents to result in higher battery voltages. Thus, the gassing region and the VR setpoints are reached at a lower state-of-charge. Raising the VR setpoint does little to ameliorate this situation, since it will simply permit more gassing. When the photovoltaic array will be regularly charging the batteries at a rate exceeding the C/20 rate, this may be a serious problem. If adding battery capacity is ruled out, then constant voltage charging should be considered.

In constant voltage charging, the amount of charge current is regulated by the controller such that the battery is held at the voltage regulation setpoint. In practice, photovoltaic charge controllers use **modified constant voltage charging**, in which charging occurs with whatever current the PV array is able to furnish until the VR setpoint is reached[1]; then constant voltage charging is used. This is shown in **Figure 2**.

The tapered current that a constant voltage controller passes at the end of charge ensures that the controller does not attempt to force more current into the battery than the battery is capable of utilizing. This sophistication tends to be reflected in more complex controller designs. In addition, in many constant voltage controllers, some or all of the power that is not being used to charge the battery must be dissipated as heat within the controller.

Many charge controllers shift the VR setpoint up or down depending on the condition of the battery. Finding the right VR setpoint is difficult: if it is too high, the battery will be overcharged often, and if it is too low, the battery will never be fully charged. One approach is to normally apply a fairly low VR setpoint, to avoid excessive overcharge, but to occasionally raise the VR setpoint, to ensure a full charge of all the cells every several weeks. This occasional full charge is called an "**equalization**" charge.

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[1] Some controllers limit the maximum current even prior to the switch to constant voltage charging.

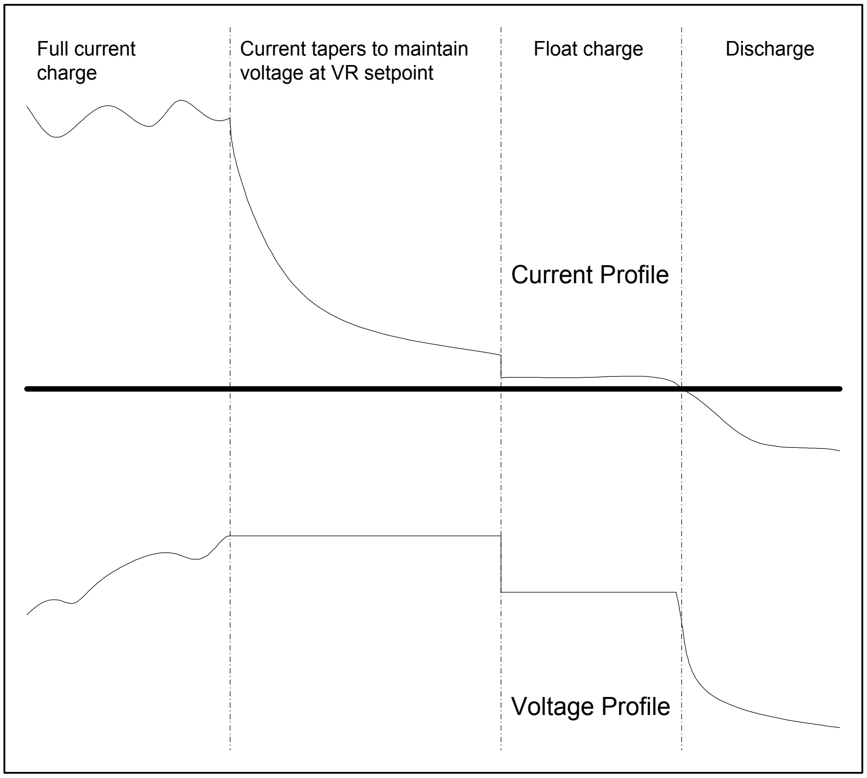

Figure 2: Modified Constant Voltage Charging

Another refinement used in many chargers is to conduct charging in **two stages**. There are a number of variations on the two stage charger. With interrupting controllers, the VR setpoint is sometimes raised following a discharge below the VRR setpoint; the VR setpoint is lowered to its normal level after the battery has been charged up to this augmented VR setpoint. This augmented VR setpoint is often called a "**boost charge**" setpoint. There are various methods of applying the boost charge; although most simply charge to the higher voltage once, then regulate at the regular VR setpoint, some controllers will use the boost setpoint for a timed period. Alternatively, the current can be applied in two stages: up to the VR setpoint, the controller permits all of the array's current to flow to the battery; once the VR setpoint has been reached, charging is finished by a low "**trickle**"current. With constant potential charging, the VR setpoint is often set relatively high, but when the current accepted by the battery drops below a certain level, the setpoint is dropped to a lower "**float**" setpoint, as shown in **Figure 2**. The float setpoint permits a small current into the battery, ensuring that it remains fully charged, while not causing excessive gassing.

On/off charging and constant voltage charging protect against overcharging. Many controllers also include a **load disconnect** to protect against overdischarging. When a battery is discharged so deeply that its voltage reaches a minimum threshold, known as the "**load disconnect**" or "**low voltage disconnect**" (LVD) setpoint, the load is automatically disconnected from the battery. When the battery has recharged sufficiently that its voltage has risen above a "**load reconnect**" or "**low voltage reconnect**" (LVR) setpoint, the load is reconnected. Since deep discharges are detrimental to the battery, the choice of LVD is a trade-off between loss-of-load probability and battery life. The LVD setpoint is sometimes current compensated for systems which supply varying loads, or temperature compensated for systems in varying climates. As with the LVD, the LVR must be chosen to minimize the period the battery is at a low state-of-charge, yet maintain acceptable load reliability. These setpoints are illustrated in **Figure 1**.

Nowadays, “smart” charge controllers are being developed. These controllers use techniques such as “fuzzy-logic” and learn about the behavior of the specific batteries they are used with. As a result, the controllers with sophisticated enough algorithms will better manage the batteries and get more out of it, both in terms of energy and lifetime. While this document does not address this particular technology, it should be noted that these types of controllers still need values, such as those given here, to start with. However, these values are normally programmed in the controller by the manufacturers of such controllers.

2 BATTERY CHARGE REGULATION

2.1 Charge Controller Configurations

Controllers are generally built in either shunt or series type configurations. As a battery approaches full charge, a shunt controller will short-circuit and a series controller will open-circuit the PV array to reduce the charging current applied to the battery. The following is a brief overview of the most common controller topologies for battery charge regulation. The principal advantages and disadvantages of these various topologies shown in Figure 3 are also summarized in Table 1.

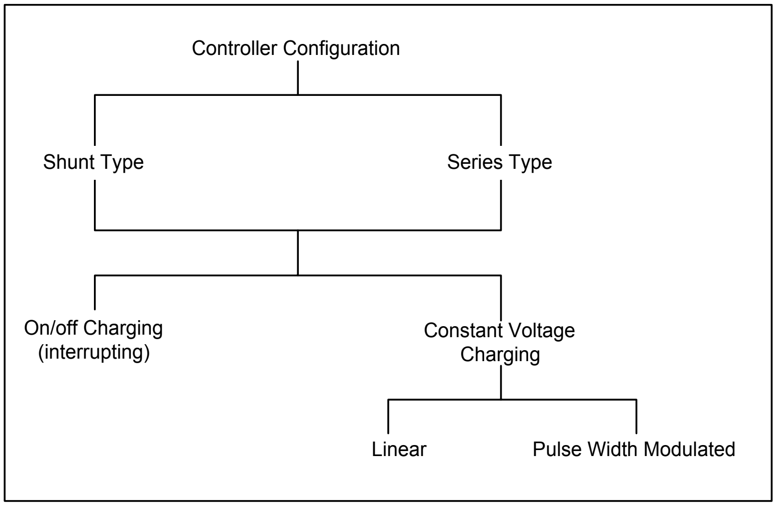

Figure 3: Common Controller Topologies for Battery Charging Regulation

Table 1: Controller Configuration Comparison

Controller Type	Charging Method	Advantages	Disadvantages
Shunt-Interrupting	On/Off	- lower voltage drop across controller than series configuration - often simple, cheap and reliable	- significant power dissipation in switching element in large systems - blocking diode required - can cause hot spots in high voltage arrays - may have difficulty fully charging battery at high currents
Shunt-Linear	CV	- tapered current charging - lower voltage drop across controller than series configuration	- significant power dissipation in switching element - blocking diode required - can cause hot spots in high voltage arrays
Series-Interrupting	On/Off	- no power dissipation required - often simple, cheap and reliable	- may have difficulty fully charging battery at high currents
Series-Linear	CV	- tapered current charging	- power dissipation required - voltage drop across controller
Series/shunt-Pulse Width Modulated	CV	- tapered current charging - lower power dissipation than other CV methods	- voltage drop across controller - generally more complex than series or shunt on/off controllers - sometimes causes electromagnetic interference in sensitive equipment nearby
Sub-Array Switching	stepped	- pseudo-tapered current charging - can control large arrays	- not cost effective with small arrays
None	self-regulated	- low-cost	- charge regulation strongly temperature dependent - charging never completely terminates

2.1.1 Shunt Type Controllers

Shunt Interrupting (On/Off)

This method, shown conceptually in **Figure 4**[2], diverts array energy to a parallel (or shunt) path when the battery reaches the full charge VR setpoint. Charging is then resumed once battery voltage falls below the VRR setpoint. This approach is not recommended for larger systems, since power losses in the switching element are high and require a means of heat dissipation. When system voltages exceed 24 VDC, shunt controllers must be used with caution, since extended periods in short circuit may cause "hot spot" damage to PV cells when many are linked in series.

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[2] In all the figures showing controller topologies, the negative side has been grounded. Most North American charge controller manufacturers recommend this, but it is not a universal practice. In addition, the topologies show switching of the positive side of the connection between i) the battery and the array, and ii) the load and the controller. In some countries, the electrical code permits simultaneous switching of both positive and negative sides of these connections, and it is reportedly encouraged. Consult local manufacturers and the electrical code.

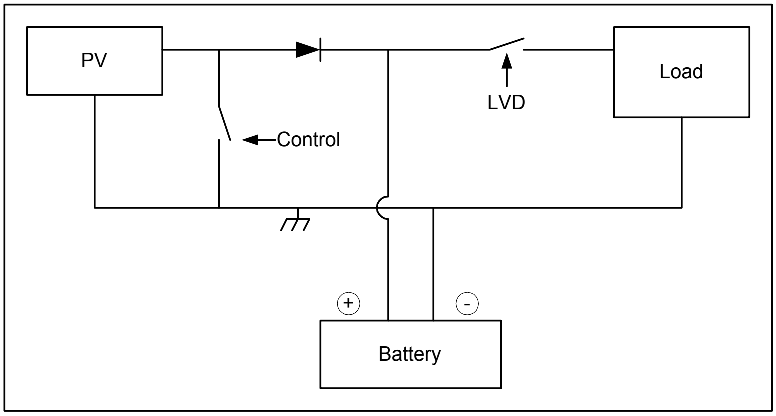

Figure 4: Shunt Control

Shunt Linear (Zener Diode)

This method uses a control element to maintain the battery at the VR setpoint as it approaches full charge. By shunting power away from the battery in a linear manner, this provides a constant voltage charge to the battery. In this controller, a zener diode with a reverse voltage rating equal to the VR setpoint is installed in parallel with the battery. When the battery voltage equals the diode voltage, the diode conducts, shunting as much current as is necessary to keep the system on a constant voltage charge.

2.1.2 Series Type Controllers

Series Interrupting (On/Off)

This method, shown in Figure 5, terminates charging at the VR setpoint with an in-series element which open-circuits the PV array. As with the shunt interrupting on/off controllers, charging is then resumed once battery voltage falls below the VRR setpoint. These controllers may, or may not, require a blocking diode depending on the switching element design.

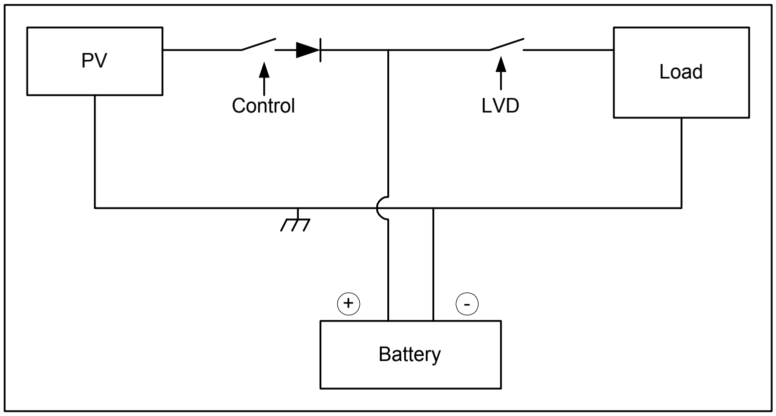

Figure 5: Series Control

Series Linear

This method applies a constant voltage to the battery as it approaches the full charge VR setpoint by using a series control element which acts like a variable resistor. This element dissipates the balance of the power that is not used to charge the battery.

2.1.3 Pulse-Width Modulation (PWM)

This method uses solid state switches to apply pulses of current at a reasonably high frequency (e.g., 300Hz), but with a varying duty cycle, such that the battery receives a constant voltage charge from the array. This type of controller, shown in a series configuration in Figure 6, can also be configured in the shunt topology. Although similar to the series linear and shunt linear controller in function, power dissipation is reduced with PWM topology compared to series linear control.

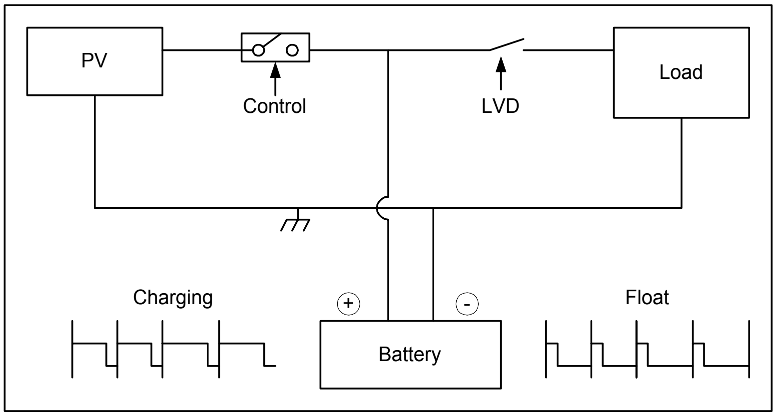

Figure 6: Pulse With Modulation (PWM)

2.1.4 Sub-Array Switching

This method, shown in Figure 7, is similar to the series interrupting circuit, except that rather than open-circuiting the entire array, sub-arrays are gradually switched out to decrease the charging current as the battery nears its end of charge. This method is used in large PV systems to supply a pseudo-tapered charge current to the battery.

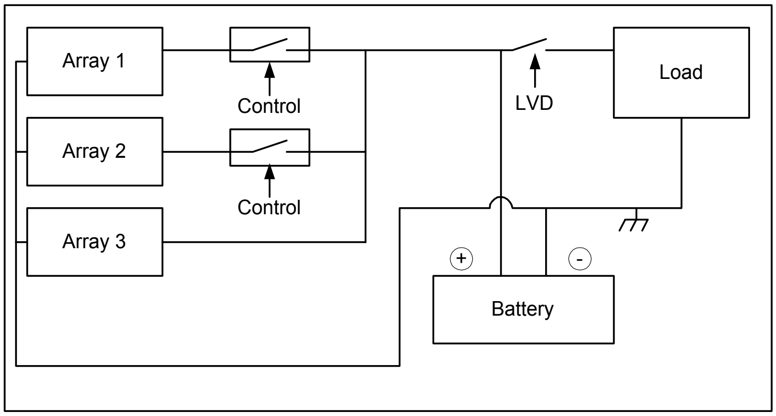

Figure 7: Sub-Array Switching

2.1.5 No Controller: Self-Regulating PV Modules

Under certain circumstances, photovoltaic systems can be designed to self-regulate, thus eliminating the need for a controller. This configuration has the IV curve of the PV module carefully matched to the operating voltage of the battery. In stand-alone systems, the battery voltage determines the system voltage and therefore the battery's state-of-charge dictates the operating point of the PV module. For crystalline silicon PV technology, a self-regulating module usually has 30 to 32 cells in series[3], 4 to 6 less than the typical module. When connected to the terminals of a 12V battery, the operating point of a self-regulating PV module is therefore closer to the knee of its IV curve and, as the battery is charged, its voltage gradually pushes the operating voltage above the knee, causing the module current to drop off (to regulate). However, due to the fact that i) module voltage is dependant on temperature, and ii) self-regulated current never completely shuts off; these modules are only appropriate for special applications. These include systems which are sited in climates with limited seasonal temperature fluctuations, and systems which include significant battery autonomy (large battery capacity for given PV array). Outside of these circumstances, a self-regulating PV module can either overcharge a battery, leading to excessive gassing, or, conversely, undercharge the battery, leading to sulfation, and both of these conditions will reduce battery operating life and system integrity.

2.2 Charge Regulation Setpoints

2.2.1 The Importance of Optimizing Charge Regulation Setpoints

Proper charging is essential if a PV system is to maintain acceptable autonomy, efficiency, and battery life. Using appropriate regulation setpoints is crucial, and often has more bearing on battery health than the actual method of charging applied (i.e., On/Off or Constant Voltage). Towards this end, the charge and discharge threshold setpoints are sometimes adjustable so that they can be fine-tuned to suit the battery and application.

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[3] Regardless of the PV technology, a self-regulating panel will have an open-circuit voltage of around 17 V to 18 V for a 12 V lead-acid battery.

If the end-of-charge VR setpoint is set too high, the battery will be overcharged and its cycle life can be diminished. Once a battery is charged above a certain voltage threshold, termed the gassing voltage, a portion of the charge is used not to carry out the desirable reactions of converting lead-sulfate to lead and lead-dioxide, but rather for the electrolysis of water into hydrogen and oxygen. In vented batteries, some electrolysis is necessary, because the gas bubbles thus created mix the electrolyte and eliminate electrolyte stratification. However, if the voltage regulation setpoint is set too high, substantial overcharging will cause excessive gassing and water loss which will lead to accelerated corrosion, plate damage and battery dry-out. Prolonged gassing can also permanently dislodge active material from the plates. In sealed batteries, for which the electrolyte cannot be replenished, excessive electrolysis will shorten battery lifetime and is usually not required for destratification (many sealed batteries used in PV systems have the electrolyte immobilized in a gel or a glass mat - the electrolyte does not therefore tend to stratify). Furthermore, it should be noted that battery efficiency is lower when cycling occurs in the gassing region since a portion of the charge current is consumed by the electrolysis reaction.

If the end-of-charge setpoint is too low, the battery will never receive a complete charge; this will decrease system autonomy and lead to negative and positive plate sulfation and electrolyte stratification.

The optimally charged battery will not spend a lot of time gassing in the overcharge region, but will make periodic visits to this region so that its electrolyte can be destratified and its cells equalized. This overcharge can result from an elevated VR setpoint, a time or low-voltage triggered boost charge (two stage controllers), or a manual or automatic equalization charge.

Some AGM and gelled batteries do not tolerate gassing well, and with these batteries the manufacturer should be consulted before boost charging or equalization are performed. A controller meant for flooded batteries should not be used to charge AGM or gelled batteries, since it may cause excessive overcharging.

2.2.2 Suggested Charge Regulation Setpoints

Table 2 gives suggested charging setpoints for a selection of battery technologies. **It must be noted that these should not be considered definitive, and that these may have to be adjusted depending on the type of battery, the type of controller, the system, the load, and where it is installed.**

In Table 2, all setpoints are given in Volts per cell (V/cell); to find the setpoint for a nominally 12 V system, for example, multiply by 6. In the third column, “boost” refers to the setpoint used once the battery has discharged below the VRR setpoint. The boost setpoint is lowered to the VR setpoint once the battery voltage has reached the boost setpoint once; alternatively, the boost setpoint can be used for a period of half-an-hour to an hour after the battery voltage first

attains the boost setpoint. Following this, the VR setpoint is used. In the sixth column, the VR setpoint is held until the current decays to a level of approximately 1 amp for every 100 AmpHrs of battery capacity; then the float setpoint is used.

Table 2: Suggested Setpoints for Various Battery Technologies
(Volts per cell at 25 °C)

	Interrupting Charging			**Modified Constant Voltage Charging**		
Battery Type	VR/VRR	Boost/VR/ VRR	Equalize VR/VRR	VR	VR/Float	Equalize VR
Flooded/ vented lead antimony	2.40/2.25	2.50/2.35/2.20	2.55/2.35 for 0.5 days every 10 to 20 days	2.35	2.40/2.25	2.50 for 0.5 days every 10 to 20 days
Flooded/ vented lead calcium	2.45/2.30	2.55/2.40/2.25	2.55/2.35 for 0.5 days every 10 to 20 days	2.40	2.45/2.30	2.50 for 0.5 days every 10 to 20 days
Flooded/ Sealed	2.40/2.25	2.45/2.35/2.20	2.50/2.30 for 0.5 days every 10 to 20 days	2.35	2.45/2.30	2.50 for 0.5 days every 10 to 20 days
AGM	2.35/2.20	2.40/2.35/2.20*	2.40/2.25 for 0.5 days every 10 to 20 days*	2.35	2.35/2.25	2.40 for 0.5 days every 10 to 20 days*
Gel	2.35/2.20	2.45/2.35/2.20*	2.45/2.25 for 0.5 days every 10 to 20 days*	2.35	2.40/2.25	2.45 for 0.5 days every 10 to 20 days*
*** Consult manufacturer before using setpoint above 2.35 Volts per cell**						

These setpoints are presented assuming that the controller is equipped to do equalization or an equalization charge is performed manually on a regular basis. If this is not the case, the VR and VRR setpoints may have to be raised by 0.05 to 0.1 V per cell; unless manufacturers state otherwise, the AGM and gel battery setpoints should not be raised by more than 0.05 V per cell, or the batteries may be dried out. During winter, there may be insufficient sunshine to fully recharge the battery for a period of time exceeding the recommended equalization period. While this is not ideal, the problem lies with the solar resource and not the controller, and the equalization setpoints should not be changed because of this.

In the setpoints recommended above, the difference between the VR and the VRR setpoint is relatively small. This will tend to encourage full charging of the batteries, but depending on the battery, may cause rapid cycling between the setpoints, especially as the battery ages. This may cause premature failure of some types of charge controller. If this is suspected the VRR setpoint may have to be lowered.

2.2.3 Optimizing Charge Regulation Setpoints

When choosing setpoints, several factors should be taken into consideration, including controller type, battery type, battery condition, application type and the frequency of maintenance visits. The influence of each of these factors is summarized in **Table 3**.

2.2.3.1 Adjusting Charge Regulation Setpoints for Controller Type

With modified constant voltage controllers, "unregulated" charging occurs until the battery voltage reaches the voltage regulation VR setpoint, after which the current is tapered such that the voltage is maintained at this setpoint. When selecting the optimal constant voltage setpoint, the goal is to minimize the time required to achieve 100% SOC without damaging the battery. Raising the VR setpoint will achieve faster charging, but at the expense of a higher gassing rate. Since the battery voltage will be held at the constant voltage setpoint, potentially for extended periods of time, it is important that the gassing rate be low at the VR setpoint. This is especially true for sealed batteries. **The VR setpoint should therefore be lower for Constant Voltage controllers than for On/Off controllers.**

Table 3 Customizing Controller VR and VRR Setpoints

			VR	**VRR**
Charging Method	No Equalization		↑	↑
	Two Stage		↓	↓
Battery Type	Vented	Pb-Antimony	↓	↓
	Sealed	Flooded Electrolyte	↓	↓
		Gelled Electrolyte	↓	↓
		Absorbed Glass Mat	↓↓	↓↓
	Plates constructed for:	Automotive (SLI)	↑	↑
		Stationary (sealed)	↓	↓
Application	Float		↓	↓
	Hybrid Cycling		↓	↓
Watering	Infrequent		↓	↓
Battery Condition	Aged or Sulfated		↑	↓

Legend: ↑ Raise ↓ Lower

2.2.3.2 Adjusting Charge Regulation Setpoints for Battery Type and Age

The type of battery technology used has significant bearing on the optimal choice of charge control setpoints. **A sealed (valve regulated) lead-acid battery will generally require lower charge setpoints than a vented battery of the same formulation, since the inability to add water to a sealed battery means that sustained overcharging will compromise battery life**. On the other hand, most sealed/flooded batteries (especially car batteries) have a fairly short lifetime, and water loss is not the life-limiting factor. Although sealed batteries are made with pure lead or lead-calcium grids and therefore have lower rates of gassing, there is still a trade-off between the periodic need for cell equalization and the damage done by gassing and the associated permanent loss of water. Many sealed batteries do recombine into water the oxygen and hydrogen gas resulting from electrolysis; this is quite efficient at low gassing rates (up to 98% recombination), therefore some equalization can be accomplished at low rates of overcharge. Stratification is not usually a problem in immobilized electrolyte batteries (i.e., gelled and AGM), the most common sealed type used in photovoltaic applications.

Calcium or antimony is generally added to lead-acid battery grids to make them more capable of withstanding deep discharges. Antimony often performs better in this function, but its addition causes increased self-discharge and higher rates of gassing, especially as the battery ages. **When using a Pb-antimony battery in a PV application, its charging setpoints should be lowered unless watering can be carried out on a monthly or seasonal basis**. Calcium is usually added to the grids of sealed batteries. It provides many of the benefits of antimony, without the increased rates of gassing and self-discharge. Low antimony formulations (2% or less in the positive grid) are also quite popular in cycling applications.

Different types of batteries are constructed differently and therefore should be charged differently. Traction batteries, intended for use in electric vehicles such as forklifts, have thick, robust plates that permit repeated deep-cycling. Often traction batteries have antimony added to them, and do not have a large reservoir of electrolyte. The amount of electrolyte generally limits the depth of discharge. Traction batteries can be charged to relatively high setpoints if they are vented and water will be added to the battery frequently. Stationary batteries, generally used to provide standby power in uninterruptible power systems (UPS), also have thick plates, but are rarely meant for deep-cycling. Generally calcium is used as a grid additive, and a large reserve of electrolyte means that the amount of active material in the plates limits the depth-of-discharge. Many stationary batteries are of sealed construction; in this case, the charging setpoints should not be high, since it will limit battery life. On the other hand, a vented stationary battery can be charged to high setpoints. SLI batteries, which provide current for starting, lighting, and ignition in automobiles, motorcycles, and small boats, are optimized for providing brief surges of current. As such, they have thin, fragile plates, calcium in the grids, and are usually of sealed construction. They do not cycle well. Even though high setpoints will cause water loss, they are often recommended, since grid and plate deterioration, and not water loss, will usually be responsible for the battery's demise. An exception to this may be in hot climates.

As a battery ages, its internal resistance often increases; sulfated batteries also have higher internal resistances. At a given state-of-charge and charge current, the aged or sulfated battery will have a higher voltage across its terminals. In order to fully charge the battery, the VR setpoint must be raised slightly; this has the undesireable side-effect of increased gassing and attendant water loss. In on/off controllers, the VRR setpoint may also need to be lowered, since the increased internal resistance of the battery will mean lower voltages across the battery terminals once the battery has reached the VR setpoint, the array has been disconnected, and the battery must power the load. This will be especially problematic when loads are fairly high (e.g., higher than C/50). If these setpoints are not adjusted, the controller will tend to oscillate between the two, possibly foreshortening battery and controller lifetimes.

2.2.3.3 Adjusting Charge Regulation Setpoints for Application Type

The application in which the PV system is to be used must be considered when choosing charge setpoints. From the point of view of the controller, PV applications are one of the following: i) stand-alone "float", ii) stand-alone cycling or iii) hybrid cycling (includes back-up generator). The setpoints used for charge control should be biased according to the type of application.

A stand-alone float application is one in which there is significant system autonomy (14 or more days) and therefore the battery spends most of its operating life in the charge regulation region at full, or near full, states-of-charge (e.g. emergency telephones or VHF repeater sites).[4] **Float type applications should have lower charge setpoints to account for the amount of time the battery will spend in the regulation region**. Boost charges for these applications should be triggered on time-elapsed limits rather than low-voltage since they will seldom be cycled to any significant depth.

Stand-alone cycling applications are those in which the system is designed with less storage (less than 14 days autonomy) and therefore the battery is expected to see both daily and seasonal cycling. A typical stand-alone cycling application is the residential off-grid cottage. When a battery is cycled often, its electrolyte tends to stratify and its individual cell voltages will begin to diverge. **Stand-alone cycling applications therefore require higher charge setpoints since the battery is not guaranteed to reach full state-of-charge regularly, and therefore when it does, charging should continue into the overcharge region to allow electrolyte destratification and cell equalization**.

Hybrid applications, which combine PV with a fossil-fuel backup supply (e.g. diesel, gas, TEG, propane) and are discussed in **Section 6**, will usually cycle the battery even more frequently than stand-alone applications (1 to 3 days autonomy). Since the battery will be continuously cycling, it will require periodic electrolyte destratification and cell equalization. This overcharge can be configured into either the PV charge setpoints or the backup charger setpoints. **However, the availability of the backup means that the battery will reach a full state-of-charge regularly, therefore, the charge setpoint need not be as high as with the stand-alone cycling application**.

In stand-alone cycling and hybrid cycling applications, discharge rates can sometimes be quite high (e.g., higher than C/30). If the battery reaches full charge at the same time that the load is drawing a lot of current[5], the voltage of the battery will drop quite drastically when an on/off controller reaches the VR setpoint and disconnects the array. In some cases, the VRR setpoint will have to be lowered to prevent this, since it will cause oscillation between the VR and the VRR setpoint.

2.2.3.4 Adjusting Charge Regulation Setpoints: Water Loss and Maintenance Frequency

Battery water loss is a common cause of PV system failure. For most systems, the dominant cause of water loss is electrolysis combined with infrequent maintenance visits. Gassing begins when cell voltages exceed the threshold at which water begins to electrolyze. Above this gassing voltage, the rate of electrolysis increases exponentially (see Figure 8). Besides voltage, this reaction is also a strong positive function of temperature, with hot batteries producing more gas at a given voltage than cold batteries.

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[4] Although a VHF telecom repeater is not technically a float application, its operation is best described as such since the daily cycling is usually only 3-5%, and the array to load ratio is typically very high (the battery is almost always at a high state-of-charge).

[5] This will be somewhat rare in stand-alone systems, since the charge current will have to be relatively high.

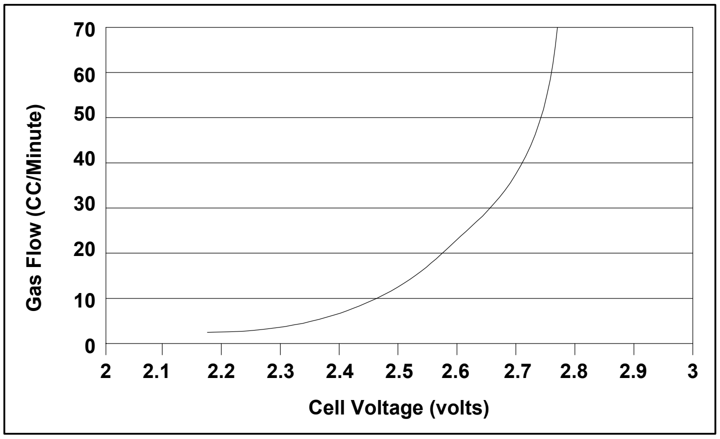

Figure 8: Example of Lead-Acid Gassing vs Cell Voltage (a particular type of flooded PbSe cell at 20°C)

This temperature dependence means that a battery's requirement for watering will often fluctuate seasonally, especially when the charge setpoints are not temperature compensated. If a battery will be installed in a hot climate, lower charging setpoints may be required, especially if battery watering will not be frequent and temperature compensation will not be used (see Section 2.2.4).

Higher charging setpoints facilitate more complete charging, at the expense of increased water loss. At sites where maintenance is available, some water loss should therefore be designed into the system in order to maintain the battery at as full a charge as possible. **If a flooded lead-acid battery is likely to be watered regularly, its setpoints can be raised slightly to assure that it receives adequate overcharge in the gassing region. If maintenance is not likely to occur regularly, then gassing should be kept to a minimum and therefore the setpoints should be lowered.**

2.2.3.5 The Importance of the Voltage Regulation Reconnect Setpoints

Although it is important to choose both VR and VRR setpoints carefully, it has been found that for On/Off controllers it is the Voltage Regulation Reconnect setpoint, and not the Voltage Regulation setpoint, which has the greatest impact on battery operation. The number of times a system cycles off and on during a day while in regulation has a much stronger positive impact on battery SOC than the maximum voltage reached in any one cycle. When the VR and the VRR setpoints are close together, the battery will cycle between them more frequently. This will result in a higher state-of-charge but a shorter switching element lifetime if a mechanical relay is used.

2.2.3.6 Determining the Optimal Charging Setpoints

Although it is not yet possible to provide an exact methodology for setpoint determination, **Table 3** summarizes what has been discussed in the previous sections. To use this table, compare the system to the base case of a vented deep-cycle lead-calcium battery in a stand-alone cycling application. **This table should be used to bias the setpoints with respect to the base case, which is a VR of 2.45 V/cell and a VRR of 2.30 V/cell for a single stage On/Off controller, a VR of 2.40 V/cell for a single stage CV controller, all specified for a**

battery temperature of 25 ºC. In the base case, equalization is performed once every two weeks. This table does not provide exact values, rather it gives an indication of how the setpoints should be adjusted based on the given application and technologies used.

2.2.4 Temperature Compensation

Most PV systems should use controllers which correct the charge regulation setpoints to the temperature of the battery. This compensation is required since the rate of electrochemical activity within a battery is strongly dependent on temperature. At higher temperatures, a battery will accept charge more quickly and will start to gas at a lower voltage. The opposite is true for battery operation at low temperatures. A controller which uses fixed setpoints will overcharge its battery in hot climates and in high current applications (ohmic losses contribute to elevated battery temperatures), and will undercharge its battery in cold climates. Temperature compensation is especially important for sealed batteries since if the final voltage is not reduced in hot climates, the battery will gas and lose electrolyte permanently.

Although it is often considered an option, temperature compensation should be incorporated into all but the smallest systems since the cost of poorly charged batteries far outweighs the cost of correcting the voltage regulation setpoints. The temperature sensor used for compensation will be internal to the controller, mounted on the battery case, or attached to the battery post. External sensors are more accurate since battery temperature during cycling can deviate significantly from ambient and from the internal temperature of the controller. This is critical for shunt configuration and constant voltage type charge controllers since considerable heat is generated internally during the regulation cycle; in some cases this can raise the temperature of the charge controller 30^{o}C above ambient. Sensors internal to the controller should be used only when the installer does not take the time to properly install an external sensor.

When used, temperature compensation should function correctly across the entire operating range of the battery. Sensors should be accurate to within 2 or 3 ºC, robust, field serviceable, and resistant to corrosive environments. Simple faults in temperature sensors or their field wiring should cause the controller they serve to revert to a safe operating mode (such as a 25^{o}C default). Under no circumstance should typical sensor or wiring damage cause the controller to fail altogether or require factory return for servicing. Where proper temperature compensation of control setpoints runs the risk of exceeding the safe operating voltage of any parallel connected equipment (e.g. battery operated DC loads) a simple yet positive means of ensuring that safe operating voltages are not exceeded should be included in the control system.

The temperature compensation factor used by most controller manufacturers is -5 mV/^{o}C/cell, which is -30 mV/^{o}C for a 12 volt battery. Note that the factor is negative - the voltage setpoint should go down as the temperature goes up. These factors are certainly applicable from -5 ºC to 35 ºC, and are often used outside this range as well.

2.2.5 Equalization Charges

Differences in the temperature and self-discharge rate of the cells in a lead-acid battery cause the state-of-charge of the cells to diverge. This condition must be periodically corrected to avoid overdischarging the weaker cells. This can be accomplished with a regular equalizing charge, which is essentially a prolonged overcharge. Besides cell equalization, this overcharge is also required to eliminate electrolyte stratification and plate sulfation.

While equalization can be carried out manually, this requires a maintenance visit every two to three weeks. An alternative is to use a controller with automatic equalization, which overcharge the battery at regular intervals or following a deep discharge. The operation of these controllers is shown in Figure 9.

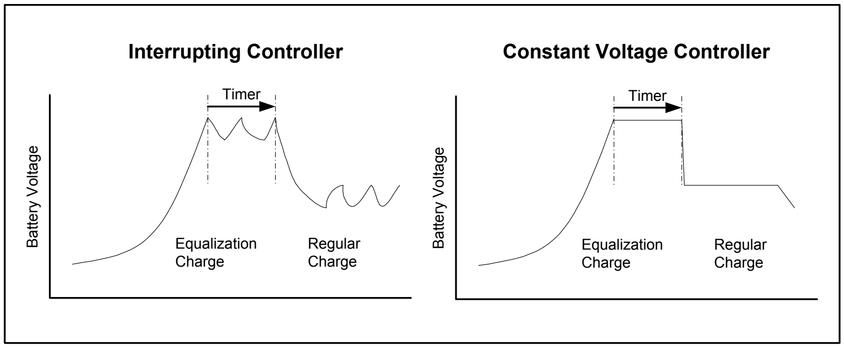

Figure 9: Battery Gassing Methods

For batteries that are cycled regularly (e.g., with a low autonomy battery), the battery should be equalized every one or two weeks (every five to ten cycles). For float service batteries, once a month is usually sufficient.

Recommended equalization setpoints are given in **Table 2**. As shown in the table, with AGM and gelled electrolyte batteries, lower setpoints should be used to limit gassing (2.4V/cell or below). It must be noted, however, that the gassing voltage of a battery, which determines the appropriate equalization voltage, varies from battery formulation to battery formulation. Thus, these setpoints may need to be lowered or raised depending on the battery.

The high rate of gassing sustained during equalization can cause catalytic recombiner caps, which recombine oxygen and hydrogen gas into water, to overheat and be damaged. Catalytic recombiner caps should be removed prior to manual equalizations; these caps may not be appropriate for systems with automatic equalization.

2.2.6 Applying the Setpoints

Merely determining the optimal charge control setpoints does not guarantee proper charging of the battery. In order for this to occur, the controller must be able to properly measure the true battery voltage, so that it can compare this with the setpoints. Many controllers read the battery voltage at the input to the controller; the resistance of the wire joining the battery to the controller will ensure, however, that there is a voltage drop between the two, especially when there is a large current flowing. This voltage drop will mask the true battery voltage, introducing imprecision into the application of the setpoints, with incomplete charging often occurring as a result.

This problem is much less serious with constant voltage chargers, two stage chargers that taper the current, and sub-array switching controllers. This is due to the lower current that flows at the end of charge: the lower the current, the lower the voltage drop across the wire, and the lower the error in the controller’s reading of the battery voltage.

For interrupting controllers, this problem can be eliminated by the use of voltage sense wires, a separate set of connections between the battery and the controller which carry no current and therefore have no voltage drop across them. In order to use voltage sense wires, the controller must have a special set of terminals where they can be attached.

An alternative approach used in some sophisticated controllers is to estimate the voltage drop between the battery and the controller on the basis of the current flow and the resistance of the wire connecting the two. This resistance must be programmed into the controller in advance.

3 BATTERY DISCHARGE REGULATION

3.1 The Argument for a Load Disconnect Feature

In a photovoltaic system, the charge controller regulates not just the charging of the battery, but in a limited sense, the discharging as well. Batteries that are cycled too deeply age prematurely. By deciding when the battery is at a dangerously low state-of-charge, and disconnecting the load at this point, the controller regulates discharge and protects the battery. The controller then waits for the battery to be recharged to an acceptable level before reconnecting the load. The circuitry which disconnects and reconnects the load in this way constitutes a "low voltage disconnect" or a "load disconnect" feature.

A battery that is deeply discharged on a regular basis tends to fail sooner-- that is, after fewer cycles-- than a less deeply cycled battery. The load disconnect is meant to ensure that the minimum state-of-charge is sufficiently high that the battery has a reasonable lifetime. While this protects the battery, it comes at a cost: the useable battery capacity is much reduced, since the capacity "below" the load disconnect is inaccessible. Thus, for a given amount of useable storage, a larger battery bank must be used. Nevertheless, it is generally more cost-effective, on a life-cycle basis, to use a large, long-lasting battery bank than a small battery bank that must often be replaced.

There is a good argument that all controllers should have a load disconnect. The additional cost, approximately $15 to $30 [Gerken et al., 1997], is usually an insignificant portion of the total system cost; the net benefit will almost certainly exceed this. Even in a system that is designed so that the probability of a deep discharge is extremely low, the load disconnect protects against overdischarge resulting from a module failure or a poor connection; while the risk of such occurrences is minimal, the cost of replacing a battery bank damaged by overdischarge can be very high.

3.2 Different Load Disconnects for Different Systems

What is the ideal depth-of-discharge at which to disconnect the load? That depends on three factors: the type of batteries being used, the type of system, and the climate that the system will be operating in.

3.2.1 Effect of Battery Type on the Load Disconnect

The internal construction of a battery differs from one model to the next. As a result, some batteries are capable of recovering from a deep discharge relatively undamaged, while others never recover their full capacity once they have been completely discharged. For this reason, manufacturers specify a maximum recommended depth-of-discharge for their batteries; the level at which the load is disconnected should not be much below this, if at all.

3.2.2 Effect of Type of System on the Load Disconnect

Different types of photovoltaic systems cycle differently. When determining the ideal depth-of-discharge at which to disconnect the load, systems can be classified in two main categories:

1. **High reliability systems**: These are systems that are designed not to fail; therefore they tend to have a large battery bank and array. Such systems tend to shallow-cycle the batteries and deep discharges occur only rarely, when there is an extended period with very little sunshine. The battery will almost never reach the depth-of-discharge that will require a load disconnect. These systems include the power systems for many industrial applications, such as telecommunications and monitoring equipment. Moderate and high latitude systems powering loads that remain largely constant year-round often fit into this category, since the system will be sized for the winter months, and during the rest of the year the battery will remain nearly fully charged.

2. **Low reliability systems**: If these systems fail to power their load for a small portion of the time, the results are not catastrophic. To lower the cost of these systems, smaller battery banks and arrays are used; the battery will frequently be deep-discharged and the load may have to be disconnected occasionally. These include residential systems, both in developing and developed countries, and non-essential lighting systems. Often these systems will power a variety of different equipment, and the load will vary depending on which equipment is being used at a given time.

The batteries in high reliability systems generally cycle very little: often they will be kept nearly fully charged for most of the year, then make one long, deep cycle during the winter. In these types of systems, therefore, the cycle life of the battery does not limit its lifetime; rather, the battery ages due to corrosion, water loss, and possibly sulfation (the transformation of the battery's active material into insoluble crystals that limit the battery capacity) during the long, deep winter discharge [Spiers et al., 1996]. The charge controller influences the rate of corrosion and water loss only through the manner in which it charges the battery, not through the load disconnect. The extent of sulfation during the winter discharge depends principally on how long the battery remains partially charged; this, in turn, is a function of load and the amount of sunshine available. The appropriate way to reduce sulfation in such systems is by designing the system to limit the duration of the period during which the battery is held at a partial state-of-charge. A load disconnect which keeps the battery above a relatively high state-of-charge could also reduce sulfation, but only at the price of frequent and long-lasting periods when the load could not be powered. This is by definition unacceptable in high reliability systems. **Thus, the load disconnect has little role to play in prolonging the life of such systems under normal operating conditions**.

When operating conditions of a high reliability system are not normal, however, the load disconnect can be instrumental in protecting the battery. In the unlikely event of a malfunctioning module, loose connection, or failure of the part of the controller circuitry that governs charging, a load disconnect can protect the battery from complete discharge, which will usually cause permanent damage. The load disconnect should be set at the level of the maximum recommended depth-of-discharge, or, if the battery is meant for deep discharges, slightly below this level. The latter practice can be justified because the battery will reach the load disconnect only under infrequent, abnormal conditions. If the battery temperature is likely to drop below -7ºC, the load disconnect should be set to protect the battery from freezing, as discussed below.

Low reliability systems will cycle the battery much more frequently than high reliability systems, and cycle life will often limit battery lifetime. In these systems, a load disconnect protecting batteries from discharges below their maximum recommended depth-of-discharge is essential to achieving reasonable battery lifetimes; more recent recommendations suggest that the load should be disconnected at a 40% state-of-charge, even for deep-cycle batteries which have a maximum recommended depth-of-discharge exceeding 60%[Sauer et al., 1997].

3.2.3 Freeze Protection

If the system will be operating in a cold climate and the batteries will not be situated in a temperature-controlled environment, the load disconnect may need to be set to protect the battery electrolyte from freezing. Depending on the battery, freezing of the electrolyte may, at worst, crack the plates, or at best, simply cause the battery to cease operating until it thaws.

When a battery charges or discharges, the density of its electrolyte changes. The electrolyte density varies linearly with state-of-charge, although it must be noted that on recharge the electrolyte will not mix until gassing at the end of charge, and there are therefore wide variations in the density of the electrolyte from point to point within the battery. The temperature at which the electrolyte begins to freeze is determined by the electrolyte's density. From this information and an estimate of the minimum temperature that will be experienced by the batteries, the depth-of-discharge at which the electrolyte will begin to freeze can be determined, as shown in Table 4; if this is lower than the depth-of-discharge at which the load would otherwise disconnect, then the load disconnect setpoint should be raised.

Table 4: Maximum Permissible Depth-of-Discharge if Electrolyte Freezing is to be Avoided

Specific Gravity of the Battery Fully Discharged and Fully Charged							
0 % SOC	1.10	1.12	1.15	1.10	1.12	1.10	1.12
100 % SOC	1.30	1.30	1.30	1.25	1.25	1.20	1.20
Temp (ºC)	**Maximum Permissable Depth of Discharge**						
-5	100%	100%	100%	100%	100%	100%	100%
-7.5	100%	100%	100%	100%	100%	100%	100%
-10	93%	100%	100%	91%	100%	87%	100%
-12.5	87%	96%	100%	82%	95%	73%	92%
-15	81%	90%	100%	74%	86%	61%	77%
-17.5	75%	83%	100%	67%	77%	50%	63%
-20	70%	78%	93%	60%	69%	40%	50%
-22.5	65%	73%	87%	54%	62%	31%	38%
-25	61%	68%	81%	48%	55%	22%	27%
-27.5	57%	63%	75%	42%	49%	13%	16%
-30	53%	58%	70%	37%	42%	5%	7%
-32.5	49%	54%	65%	32%	37%	0%	0%
-35	45%	50%	60%	27%	31%	0%	0%
-37.5	42%	46%	56%	22%	26%	0%	0%
-40	38%	43%	51%	18%	21%	0%	0%
-42.5	35%	39%	47%	13%	16%	0%	0%
-45	32%	36%	43%	9%	11%	0%	0%
-47.5	29%	32%	39%	5%	6%	0%	0%
-50	26%	29%	35%	1%	2%	0%	0%

3.3 Voltage Setpoints to Achieve Load Disconnection at a Desired SOC

Based on the battery type, the battery's recommended maximum depth-of-discharge, the system type, and the potential for electrolyte freezing, the appropriate state-of-charge for load disconnection can be determined, as discussed in Section 3.2. On the other hand, the load disconnect setpoint takes the form of a minimum voltage. Thus, the desired minimum state-of-charge must be translated into a voltage setpoint.

As a lead-acid battery discharges, its voltage drops. This makes estimating the battery state-of-charge on the basis of the battery voltage feasible. Several factors complicate this: the rate of discharge (i.e., the current), the battery temperature, and the condition of the battery all influence its voltage. Furthermore, above a 70 % depth-of-discharge, the drop in the voltage versus time discharge curve of a lead-acid battery is not drastic; this means that determining the exact state-of-charge on the basis of the voltage alone is impossible.

A battery has an internal resistance to current flow. When a battery is being discharged, the current flowing through this resistance creates a voltage, which results in the battery voltage under load being lower than the open circuit voltage. The higher the current, the lower the voltage. Most photovoltaic systems have at least several days of battery storage, so that if the load is fairly constant, the current will be very small compared with the size of the battery, and the voltage drop due to the resistance is nearly insignificant. The voltage drop can be significant, however, if loads vary and reach levels greater than the C/30 current. This means that the voltage setpoint will disconnect the load at a higher state-of-charge when the load is higher. **Table 5** contains low voltage disconnect setpoints corresponding to different maximum desired depths-of-discharge at various discharge rates. These should be considered as approximations only.

This can be accommodated in several ways. The simplest is also the most conservative: choose the setpoint based on the lowest current, and then accept that at higher currents the load will be disconnected at a higher state-of-charge. The only disadvantage with this stems from the frequent and premature load disconnects that may occur if the battery is often discharged at a high current. Alternatively, the setpoint can be chosen on the basis of a higher current; this will result in deeper than desired cycling, and the concomitant accelerated ageing. The most elegant approach is to compensate the setpoint for the voltage drop due to the current. Since this is not required in most applications, few controllers are capable of this.

The battery's resistance to current flow is affected by the temperature and condition of the battery. At lower temperatures, the chemical reactions within the battery are hampered, and the battery's internal resistance rises. This is generally not a consideration for high temperatures, because there is a lower limit to the battery's internal resistance, but it can become important when the battery is very cold. Once again, this will not be significant at low current rates, but will cause premature disconnection at higher currents. **Selecting the setpoint based on the discharge curve at a relatively warm temperature (e.g., 25ºC) is a conservative approach**. Temperature compensation of the load disconnect setpoint is also possible, though rarely done. Older batteries and relatively new batteries which are stratified or sulfated will have a higher internal resistance than the same battery in good condition. Selecting the setpoint based on the discharge curve for a new battery is a conservative approach and common practice.

Certain loads, such as motors, can have a very high transient current draw when the load is turned on; this will cause a momentary drop in the battery voltage. In order to ensure that such momentary voltage drops do not cause unnecessary load disconnection, the controller should disconnect the load only when the voltage has resided below the LVD threshold for a minimum elapsed time; 0.5 to 2 seconds appears to be satisfactory [Gerken et al., 1997].

Table 5: LVD Setpoints (in V/cell) as a Function of Discharge Rate and Desired DOD (for 25ºC)

Maximum Desired DOD	Discharge rate			
	C/200	C/60	C/20	C/10
10 %	2.15	2.13	2.11	2.08
20 %	2.13	2.12	2.09	2.07
30 %	2.11	2.10	2.07	2.05
40 %	2.08	2.08	2.05	2.04
50 %	2.06	2.05	2.03	2.01
60 %	2.03	2.02	2.00	1.99
70 %	2.00	1.99	1.98	1.96
80 %	1.96	1.96	1.95	1.93
90 %	1.92	1.92	1.91	1.89
100 %	1.80	1.80	1.80	1.80

3.4 Load Reconnect

Once the load has been disconnected, the battery will have the opportunity to recharge. At some point in time the load must be reconnected by the controller. The load reconnect setpoint, while usually given little mention, is actually very important to achieving acceptable battery lifetimes and system operation that is satisfactory to the user.

From the user's perspective, the load should be reconnected as soon as possible. If the load is reconnected soon after disconnection, however, it is likely that the conditions of load and insolation that caused the disconnection will still exist, and probably the load will have to be disconnected again. In order to minimize this cycling, the load reconnect is generally set to permit at least a few hours of charging before the load is reconnected.

Like the load disconnect setpoint, the load reconnect setpoint is generally specified as a voltage; sometimes it is specified as a "hysteresis", or voltage difference between voltage reconnect and voltage disconnect. The appropriate setpoint will depend on how much charge should be returned to the battery before load reconnection, and, for the reasons described in Section 3.3, the charge current, the battery temperature, and the battery condition.

3.4.1 Current Compensation

Unlike discharge current, which tends to be relatively low in photovoltaic systems, charge current can vary from zero to relatively high levels, depending on the insolation. The varying voltage drop that results from this complicates selection of the appropriate load reconnect setpoint. The simple and conservative solution is to select the setpoint on the basis of a high charge current; the elegant solution is to perform current compensation. Choosing a setpoint on the basis of a low charge current is also reasonable: if the charge current is higher, the battery will reach the setpoint prematurely, but probably the current will be sufficient to meet the load and continue charging. Table 6 shows the load reconnect voltage setpoints that will roughly achieve a given state-of-charge. At a minimum, the load reconnect setpoint should raise the state-of-charge 10 to 20 % above the state-of-charge at which it was disconnected.

Table 6: LVR Setpoints (V/cell) to Achieve a Desired SOC, as a Function of Charge Rate (25°C)

SOC	DOD	Charge Rate			
		C/10	C/20	C/60	C/200
0%	**100%**	2.08	2.05	2.01	1.98
10%	**90%**	2.09	2.07	2.03	2.02
20%	**80%**	2.12	2.10	2.07	2.05
30%	**70%**	2.15	2.13	2.10	2.09
40%	**60%**	2.19	2.17	2.14	2.12
50%	**50%**	2.23	2.21	2.17	2.16
60%	**40%**	2.27	2.25	2.21	2.20
70%	**30%**	2.34	2.32	2.27	2.25
80%	**20%**	2.43	2.43	2.34	2.31
90%	**10%**	2.61	2.60	2.47	2.45

3.4.2 Temperature Compensation

Temperature compensation of the load reconnect is more important than temperature compensation of the load disconnect, for two reasons. First, since a typical photovoltaic system has to return to the battery in five to ten hours of bright sunlight what is discharged over a 24 hour period, maximum charge currents will typically exceed maximum discharge currents, except when loads are extremely variable. Second, not accounting for the increased resistance at lower temperatures is conservative for the load disconnect but reckless for the load reconnect. As a first approximation, it is reasonable and recommended to apply the same temperature compensation as is used for the voltage regulation setpoint.

3.4.3 Cycling Between Load Disconnect and Load Reconnect

Even when an appropriate load reconnect setpoint has been chosen, the possibility of cycling between load disconnect and load reconnect exists. The charge controller should be designed to reduce this cycling. A load that frequently cycles on and off will annoy the user, raise questions about whether the system is functioning correctly, and probably leave the impression that photovoltaic systems are unreliable. More importantly, cycling a battery between two partial states-of-charge soon causes severe electrolyte stratification, almost certainly causing accelerated aging of the bottom part of the battery plates [Sauer, 1997]. As the stratification worsens, the apparent capacity of the battery will decline, and all other conditions held constant, the battery will reach its load disconnect and reconnect voltage setpoints more quickly: cycling will accelerate.

Raising the load reconnect will lower the probability of such cycling, but will result in a longer period during which the load will not be powered. In high reliability systems, loss-of-load and the conditions that lead to it should be quite rare, and the probability of extended cycling will be low: it should not be long before the system begins to operate as it was designed to operate. Furthermore, in such systems, the cost of a loss-of-load is very high; otherwise, the significant additional cost of purchasing a high reliability system could not be justified. Therefore, raising the load reconnect in such systems is discouraged.

In low reliability systems, on the other hand, there is a reasonable probability that extended cycling will occur; indeed, if it is a residential system it will be at the mercy of the user, and cycling between load disconnect and load reconnect could continue indefinitely, or at least until the battery dies. In addition, loss-of-load is not that costly in low reliability systems. **Therefore, an elevated load reconnect is recommended for such systems**. Furthermore, it is recommended that the controller monitor what happens following the initial load disconnect: if a further two load disconnects occur without the battery having reached full charge in the meantime, the controller should not reconnect the battery until a full charge with equalization is performed. Obviously, this requires a fairly sophisticated controller; if the controller is unable to do this, it is recommended that the load reconnect setpoint be set to a level fairly close to the voltage regulation setpoint. It should be noted that this is not done by most existing controllers.

3.5 Optimizing LVD and LVR Setpoints

Table 7 summarizes the influence of various factors on LVD and LVR setpoint selection. To use this table, compare the system to the base case of a vented deep-cycle lead-calcium battery in a stand-alone cycling application. **This table should be used to bias the setpoints with respect to the base case, which is a LVD of 2.00 V/cell and a LVR of 2.20 V/cell, both specified for a battery temperature of 25 ºC**. **In the base case, equalization is performed once every two weeks**. This table does not provide exact values, rather it gives an indication of how the setpoints should be adjusted based on the given application and technologies used.

Table 7 Customizing LVD and LVR Setpoints

			LVD	LVR
Charging Method	No Equalization		-	↑
Battery Type	Vented	Pb-Antimony	↓	↓
	Sealed	Flooded Electrolyte	↑	↑
		Gelled Electrolyte	↑	-
		Absorbed Glass Mat	↑	-
	Plates constructed for:	Automotive (SLI)	↑↑	↑↑
		Stationary (sealed)	↑	↑
Application	Float		↓	↓
	Hybrid Cycling		↑	↑
Battery Condition	Aged or sulfated		-	↑
System Reliability	High Reliability Required		↓	↓
	Low Reliability Acceptable		↑	↑

Legend: ↑ Raise ↓ Lower - no adjustment

3.6 Actions to be Taken if the Load is Disconnected Too Often

If the controller disconnects the load frequently, it may be an indication of a problem with the system or an undersized photovoltaic array. The first action to be taken is to verify that all components in the system are operating correctly and properly connected. In particular:

1. Ensure that the array is undamaged, properly connected and has reasonable operating voltage and current when the battery is being charged.

2. Ensure that all connections at the battery are secure and that no debris or dirt on the batteries could permit current to leak to ground or between the terminals. Check the battery electrolyte level.

3. Ensure that the controller is properly connected and is operating correctly. If possible, verify that all setpoints are as specified; this includes charge regulation setpoints, since incomplete charging will result in more frequent load disconnects.

4. Ensure that the load has not malfunctioned, and is not drawing more current than it should.

5. Check the capacity of the battery, especially if the battery is old. The capacity of a battery declines at the end of its life, and this will result in more frequent load disconnects.

6. Verify that the charge controller is capable of fully charging your battery when operating correctly; this is especially worthwhile if the charge regulation setpoints of the charge controller are low compared with most others on the market.

Once it has been demonstrated that all components are functioning correctly, individually and as part of the system, one can conclude that the problem lies in the design of the system: the system is not sufficiently large to meet the load. Often the most economical solution to this problem is to reduce the load, either by eliminating some part of the load or by obtaining more efficient equipment. In some cases, where the shortfall of the system is minor, simply raising the load reconnect setpoint may ameliorate the situation. If these approaches are not successful, then the battery bank or the array size must be increased. In theory, increasing the size of either the battery or the array will increase the reliability of the system; generally, however, the system reliability will be more sensitive to changes in one or the other. Simulation is an accurate approach to evaluating the best way to increase the system reliability; for those who do not wish to do this, comparing the array to load ratio and the days autonomy of the battery can be instructive. If one seems quite large and the other quite small (compared with typical values, not with one another), increasing the small one will probably have greater impact. If it appears that increasing the array or increasing the storage would work equally well and cost approximately the same amount, the former may be preferable, since adding a new battery to a set of aged batteries is not generally recommended.

4 CONTROLLER FEATURES

Besides controlling charge and discharge current through regulation circuits, controllers can include other features and perform a variety of other functions. Some of the more common are listed below; status indicators and time delays should be considered as essential features, while the rest are optional.

Status Indicators

All charge controllers should include some sort of status indication. As a minimum, LEDs should signal correct controller operation, a low battery state-of-charge condition, and a LVD battery disconnection. Other options for status indication include LCD displays for battery parameters, meters and diagnostic indicators for regulator operation, especially indicating when the battery is performing boost charging or equalization.

Time Delays

Setpoints which incorporate time delays prior to state changes reduce nuisance tripping and/or rapid oscillations under unusual operating conditions. This is particularly important with LVD disconnects, which can trip during large transient loads, notably motor startups.

Maximum Power Point Tracking

In most systems, the battery is connected directly to the photovoltaic array through the charge controller. In these systems, the battery voltage determines the operating voltage of the photovoltaic array. Usually, this operating voltage will be close to but not exactly at the voltage at which the photovoltaic array generates maximum power. Thus, some of the power that could potentially be charging the batteries is not being used. A maximum power point tracker is an electronic circuit within the charge controller that ensures that the operating voltage of the array is at the point at which the array generates maximum power. At the expense of a more complex controller, this generates around 5% to 10% more charging current. The purchaser should verify that this gain is not lost through a high quiescent current draw.

Adjustable Setpoints

For controllers which are to be installed by knowledgeable personnel, the ability to adjust voltage regulation and low voltage disconnect setpoints allows a system to be better configured for a particular application. The setpoints may be adjusted by potentiometers (Pots), by DIP switches or by jumpers on the circuit board. Whatever the method, it should be simple enough to be set in the field without the need for special tools or training. The setpoint should be easily discernable during adjustment, either by a calibrated dial, a dip switch, or a direct digital readout. It is preferable that controllers which use temperature compensation display the controller's compensated setpoint instead of, or as well as, the nominal 25^{o}C reference value. When the user is adjusting the setpoint, however, it is preferable that the 25 ºC reference value is modified directly, rather than the temperature compensated setpoint.

Voltage Sense Wires

Separate voltage sense wires are used in charge control circuits to reduce the influence of the voltage drop in the battery leads on charge operation (battery voltage is measured at the battery terminals, rather than at the controller); these are especially important with on/off controllers. In the event of sense wire failure, it is essential that the terminal voltage of the battery at the controller be used for control purposes. Voltage sense wires are less important with constant voltage controllers, because at the end of charge the current will be tapered, resulting in lower voltage drop in the battery leads and therefore less error in the charge controller's reading.

Low and High Voltage Alarms

Low-Voltage Alarms (LVA) and High-Voltage Alarms (HVA) may be included in a controller to monitor battery voltage and send an audible, visual or electronic alarm if the battery voltage drifts beyond some predetermined safe range. The voltage setpoints should be chosen so that the system can continue to operate until a service call can be arranged (audible beepers, where incorporated, should have manual override switches). The LVA device only monitors battery voltage; even if there are multiple sub-arrays connected to one battery bank, only one LVA is required.

Self-Test

The controller may incorporate a simple means of self-test type field verification to permit installers/users to readily determine if the unit is functioning as intended.

Data-Logging and Modem Access

Microprocessor based controllers sometimes offer the possibility of multi-channel data logging which can be used to assess performance and diagnose system failures. This logging usually monitors the energy balance (PV production, battery in/out, delivered load) continuously and saves data in an EEPROM on an hourly, daily or monthly time scale. If modem access is also provided, a user can download logged data and change the system configuration setpoints remotely.

Load Management Options: Excess Power Diversion

In a typical stand-alone PV system, the array will be sized to supply enough power during worst-case conditions. As a consequence, most of the time there will be excess power beyond that which is needed to charge the battery. Instead of being dissipated as heat in controller, this excess power can sometimes be put to good use in a secondary, nonessential load, such as a fan, a pump, or a heating element. Some controllers are capable of diverting excess power to a nonessential load.

Load Management Options: Essential and Nonessential Loads

A PV system may power a number of different loads; some of these may be more essential than others. When the PV system is unable to power all these loads and the battery is approaching a low state-of-charge, a useful feature is the ability to disconnect the nonessential loads while continuing to power the high priority loads. This requires two LVD setpoints-- a high one for the low priority loads and low one for the high priority loads.

5 SELECTING A CHARGE CONTROLLER

5.1 Controller Design and Construction

Sizing the Controller

A charge controller should be sized to pass the expected continuous current from the array (or sub-array) into the battery, and should be able to withstand temporary peak currents due to sunnier than normal conditions. It is critical that the controller be adequately sized since the costs associated with controller failure are much greater than the cost of initially installing a slightly larger controller. A module will normally have a maximum current output which is near its rated short circuit current (when battery voltage is low). It is possible for irradiance levels to reach 1300 watts/m^2; the short circuit current is normally rated for irradiance levels of 1000 watts/m^2. Charge controllers should be sized, therefore, to regulate up to 130% of a module's nominal short circuit current. The size of a controller can be calculated by multiplying the I_{sc} current of a module by the number of modules in parallel and the 1.3 safety factor. Consult with controller manufacturers to determine if they have already built a safety factor into their rating value; oversizing by 130% may not be necessary if the controller is already designed to handle higher than rated currents.

Power Handling

All power handling elements should be sufficient for the service intended and should be capable of continuous operation at 130% of the nominal design current, and 200% of the nominal design voltage on both input and output. For smaller systems, the switching relay will usually be solid state and will be an integral part of the controller. For larger systems, the switching relay(s) will usually be mechanical (coil or mercury type) and will often be separate from the controller. The service life of mechanical type relays ranges from 10^4 to 10^6 cycles and of solid state type relays is not limited by the number of cycles. Depending on the charging methodology, controllers will switch between 10 and 100 times per day when in charge regulation (3×10^4 to 3×10^5 times over ten years), therefore the relay is the element within the controller which is most likely to cause controller, consequently system, failure.

Power Consumption

The standby (i.e., parasitic, quiescent, tare) current which is consumed by the controller varies, usually ranging from 1 to 20 mA, although larger units may have significantly higher consumption. Since the standby current is influenced by controller size, it is useful to determine the Standby Loss Factor[6] when evaluating a controller's power consumption. Assuming a PV system's installed capacity is equal to the charge current rating of a controller, and based on a site which has five hours of peak sunshine daily (5 kWh), this method gives values for energy loss as a percentage of collected energy which range from 0.03% to 5% for controllers currently on the market. This factor represents the minimum energy consumption of the controller. Other than standby current, controller efficiency will also depend on the voltage drop across the elements in series with the charging circuit (e.g., blocking diode) and from individual controller elements with varying duty-cycles (e.g., LEDs, relays).

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[6] Standby Loss Factor = (Standby Current * 24) / (Average Daily Peak Sun Hours * Controller Current Rating) [%]

Setpoint Accuracy

All controller setpoints should remain stable to within 2% of their intended value over the entire operating range, electrical environment, and life of the system. It should be verified that the voltage drop between the battery and the controller will not cause unacceptable errors in the controller's reading of the battery voltage. If this is found to be the case, then a controller accommodating voltage sense wires should be selected.

Thermal Design

It should be possible to install the controller in unventilated Nema or IP enclosures without the requirement for additional heat sinking or fans. When heat sinks are used, to allow proper convection, the controller should be mounted such that the heat sink has its fins running vertically.

Fail-Safe Operation

In most applications, the controller should be designed to allow continued system operation under typical failure modes. For example, in series relay switching PV charge controllers, failed relay operation should favour continued charging of storage batteries rather than PV array shutdown. The exception to this is for applications where the user or operator of the system has very little knowledge of photovoltaics and little incentive to make sure that it continues to operate. In these cases, the user is likely to notice a problem only when power no longer flows from the system. Thus, if the controller is designed for fail-safe operation and the batteries continue to be charged, the user will likely not notice and the batteries will probably fail prematurely due to overcharge.

Controller Protection

Due to their direct proximity to "lightning attractive" PV arrays and array wiring, controller designs should be highly immune to induced transients. All incoming lines to control electronics, printed circuit boards and other voltage or current sensitive components must include reasonable forms of overcurrent and overvoltage protection - including protection for the protective devices themselves. In order to increase surge immunity to the maximum extent possible, PV array power handling elements (relays, solid state switches, blocking diodes) should not be incorporated on or near the printed circuit board which contains the control electronics. Properly rated, fused and configured MOVs, tranzorbs, zener diodes, gas discharge tubes, spark gaps, inductors, etc. may be sufficient for this purpose. Controller operation should also be immune to electrical noise since operating environments are rarely "pure DC".

All controllers should have reverse polarity protection. Advanced controllers should have overtemperature protection. To prevent overvoltage damage to the load, the controller should not allow the PV array to directly supply the load if the battery is accidentally disconnected from the system.

Reverse Current Protection

Effective means of reverse current leakage protection should be provided to prevent the batteries from discharging through the PV array at night. The method used should be simple in concept, not require mechanically active components, and should limit the backfeed plus all parasitic losses to less than 1% of the daily average PV generated ampere-hours.

Ease of Installation

Unless this would render the controller unaffordable to the intended user, controllers which have more than 6 terminal connections should incorporate unpluggable terminal strips in order to eliminate the need for complicated disconnection procedures during field servicing or controller changeout. Terminal connections must be easily accessible and should not require any sort of field disassembly. The terminals should be able to accept large wires, permitting the user to oversize the wire and minimize the voltage drop in the wiring.

Warranties and Certification

Warranties on controllers vary widely, with some as short as one year and others as long as ten.; some are even warrantied for the life of the PV system. Controllers installed in residential buildings should have appropriate safety certification (see Section 9).

5.2 Selection Criteria

The following list provides some basis for determining what specifications need to be addressed when selecting a charge controller. Selection criteria and procurement specifications for charge controllers may include:

CONTROLLER SELECTION CRITERIA

- **Type of controller (e.g., Constant Voltage or On/Off)**
- **Number of charging steps (e.g. single stage, 2 stage)**
- Type of battery to be charged
- Operating temperature (e.g., from -30°C to 70°C)
- Nominal charging requirements (e.g. 130% of Isc current, 200% of Voc voltage)
- Temperature compensation, internal or external sensor
- Parasitic power consumption
- Voltage Regulation (VR) setpoint
- Voltage Regulation Reconnect (VRR) setpoint
- Low Voltage Disconnect (LVD) setpoint
- Low Voltage Reconnect (LVR) setpoint
- Adjustability of charging and low-voltage disconnect setpoints
- **Load management features (e.g., priority load shedding)**
- Optional relays for alarms, backup system startup, etc.
- Type of switching elements (solid state or mechanical)
- Reverse polarity protection
- Overcurrent protection; lightning protection
- Mounting provisions
- Input and output terminals, size and type
- Materials; corrosion resistance; NEMA/IP rating
- **Reputation of manufacturer and availability of technical support**
- Shipping requirements (e.g., shipping/storage temperature)
- Stock and parts availability
- **Dimensions and weight**
- Cost and Warranty

6 HYBRID SYSTEM CONTROL

6.1 Hybrid Systems and Gensets

Hybrid systems incorporate more than one type of electric generator. In addition to photovoltaics, they may include wind turbines, micro-hydro generators, thermo-electric generators, and fossil fuel-powered generators. When hybrid systems rely on renewable energy alone, they generally have no control over power generation: they can do nothing to influence the wind, the sun, or the rains. For these systems, charge and discharge control is largely the same as in systems with photovoltaic generators only. On the other hand, when hybrid systems contain generators which can supply power on demand, the situation is very different. Usually, the generators which are supplying power on demand are fossil fuel-powered generators, or "gensets". When renewables alone are unable to meet the load, the genset can be switched on; if there are no equipment failures, the loss-of-load probability falls to zero.

In hybrid systems, one objective of charge and discharge control is to maximize the battery lifetime, just as in stand-alone PV systems. When power on demand is added, a second objective is the minimization of the cost of genset fuel and maintenance. This chapter will concentrate on hybrid systems incorporating gensets, and therefore focus on strategies for reducing fuel and maintenance costs. A block diagram of typical PV/Genset-hybrid battery charging system is shown in **Figure 10**.

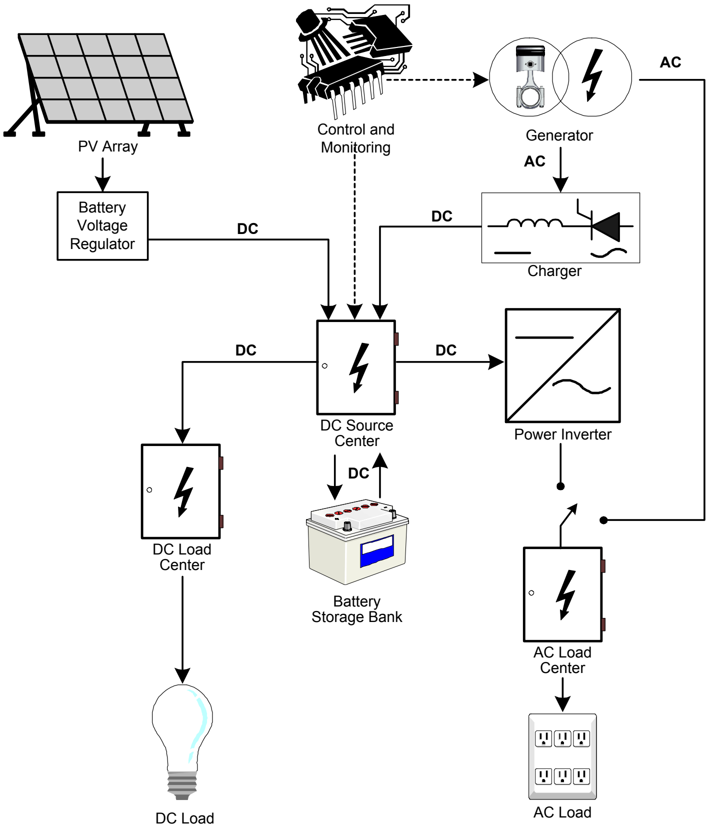

Figure 10: Typical PV/Genset Hybrid Battery Charging System

6.2 Control of a Hybrid System

In hybrid systems, “control” refers to three different aspects of system operation:

1) Dynamic control: maintaining the characteristics of the output waveform at desired levels regardless of the load and the power being produced by the different generators.

2) Charge control: regulating the flow of current to the battery, especially at the end of charge.

3) Dispatch: for systems with power on demand, determining when the genset should be turned on and off.

Dynamic control is a complicated subject quite unrelated to the charging and discharging of batteries, and is therefore outside the scope of this document.

6.3 Charge Control

In many ways, charge control for hybrid systems is very similar to charge control for photovoltaic systems. Four important differences do exist, however. First, hybrid systems tend to have relatively small battery banks which are cycled more than typical photovoltaic battery banks. This increases the danger of stratification if the batteries are not regularly equalized, and generally ensures that it is the cycle life that limits the battery lifetime. Second, when power is available on demand, many of the vagaries associated with charging from an intermittent power source are eliminated, simplifying charge control. Third, hybrid systems are typically used for bigger loads than photovoltaic systems. As a result, they are often fairly costly compared with, say, a small residential photovoltaic system. This means that the controller can be more expensive, and have more functionality, without significantly increasing the system price. Fourth, charge currents can be quite high, especially if the genset is oversized.

The danger of electrolyte stratification resulting from the frequent cycling of hybrid systems necessitates frequent equalization. This becomes increasingly important as the size of the battery bank declines relative to the load. Fortunately, very small battery banks are generally used only with systems having power on demand. The genset facilitates regular and complete equalization in a way that an intermittent power generator can not.

While battery manufacturers are often unable to recommend appropriate charge control methods for photovoltaic systems, they are usually quite familiar with the regular cycling operation of their battery. Thus, they are generally able to recommend appropriate charge methods and frequency of equalization for their batteries used in hybrid systems. Furthermore, hybrid system controllers are often sufficiently sophisticated that these recommended practices can be followed without much trouble.

If the manufacturer is unable to recommend a method of charging, the following guidelines can be used as a starting point.

1) If the system tends to discharge deeply and/or operate for long periods at partial states of charge, perform an equalization charge at a frequency of once every ten days, for systems

with less than three days of autonomy, to once every two weeks, for systems with three or more days of autonomy. Most systems should employ equalization.

2) For equalization, hold the battery at approximately 2.45 to 2.50 Volts per cell for five hours for vented batteries; at approximately 2.40 to 2.45 Volts per cell for five hours for sealed flooded or gel cell batteries; or at approximately 2.35 Volts per cell for eight hours for absorbed glass mat ("AGM") batteries.

3) When not performing an equalization charge, terminate charging by tapering the charge to sustain a constant voltage of 2.35 Volts per cell (vented batteries), or 2.3 Volts per cell (sealed batteries).

Note that all these setpoints are specified assuming a battery temperature of 25 ºC; they should be temperature compensated as in photovoltaics-only systems.

In hybrid systems, more than one generator may be providing power at any given time. It is possible to use one charge controller for each generator, but it is preferable to use a single controller for the entire system. While this single controller may be a more complicated device, there are problems that may arise when more than one controller is independently charging the battery. First, it is difficult to ensure that equalization occurs at the desired interval. Second, if different controllers use different setpoints, at best, energy will be wasted and, at worst, damage to the controllers could occur. Many hybrid systems supply AC power; a recent trend has been to incorporate a sophisticated charge controller into the inverter, eliminating the above problem.

In systems with power on demand, load disconnection does not occur, since a genset can be started instead. In hybrid systems relying on renewable energy sources only, the controller must include a load disconnect. The recommendations of Section 4 are applicable to such hybrid systems.

6.4 Overview of Dispatch Strategy

Dispatch strategy refers to the criteria by which the controller decides when the genset of a hybrid system is turned on, at what loading it operates, and when it is turned off. In practice, especially with small hybrid systems, dispatch strategies are quite simple. The genset is usually turned on automatically when a low voltage setpoint is reached, and runs until the battery reaches a voltage setpoint, the battery is fully charged, or a preset minimum run time of, say, several hours has elapsed. Many controllers also start the genset when the net load (load current minus current available from renewable energy generators) exceeds a certain level; sometimes it is left to the user to start the generator manually when this condition exists.

In most hybrid systems, the genset runs at full loading: any power not required by the load contributes to battery charging. Partial loading of the genset occurs only when the battery is approaching full charge and can not accept the full current from the genset. In some systems, however, the genset turns on only when the load is reasonably large, and then runs at the loading which supplies just enough power to keep the batteries from being discharged (i.e., it supplies power equivalent to the load power minus the power available from other generators).

In certain hybrid systems, the battery is used only to buffer transients in demand, and therefore there is no real dispatch strategy. The genset runs at all times, supplying the average of the difference between the load and the power available from renewable sources. When there is a brief demand for more power, a small battery makes up the shortfall; it is recharged when the load drops. This “**peak shaving**” mode of operation makes sense in hybrid systems with multiple gensets, since the number of gensets on-line is determined by the loading level associated with the average, as opposed to the maximum, shortfall in power.

6.5 Optimizing Dispatch

In most systems, dispatch strategies are implemented with operating setpoints that have been selected by rules of thumb. While these setpoints may work, they generally will not achieve least-cost operating of the system. There are, however, methods which can help select optimal strategies and setpoints. It is important to note that most hybrid system controllers currently available are sufficiently sophisticated that they can implement optimal dispatch strategies; the challenge is the selection of the strategy, not its implementation.

An optimal dispatch strategy is one that minimizes the life-cycle cost of the hybrid system. Dispatch strategy influences costs associated with:

1) Genset fuel use: As a first approximation, the more energy supplied by the genset, the more fuel it will use. It should be noted that gensets operate most efficiently at full loading; when without a load, they still consume one-quarter to one-third as much fuel as at full loading, and therefore are extremely inefficient. Fuel consumption varies roughly linearly between no load and full load [Skarstein et al., 1989].

2) Genset maintenance: Operating a genset causes wear to the genset. Operating it at low loading levels causes even more wear, due to incomplete combustion. Starting a genset causes wear, as well. If the genset is already near its operating temperature, the additional wear of a start is equivalent to one to four minutes of run time [Bleijs et al., 1993], which is usually insignificant. If the generator has had time to cool down, however, considerably more wear will be caused; if ambient temperatures are low (e.g., below 0ºC), the wear caused by starting can be very significant. Thus, cold starts should be minimized.

3) Battery life: Cycling a battery causes the battery to age. Keeping the battery at a low state-of-charge for a prolonged period causes sulfation, which may result in premature battery failure.

The influence of dispatch strategy on genset maintenance and battery life is especially difficult to quantify.

Examining these costs, several aspects of optimal dispatch strategy become obvious. Minimizing fuel use is essentially equivalent to maximizing the use of the renewable energy sources. If the dispatch strategy uses the genset to charge the battery to a high state-of-charge, then the battery will be unable to store excess renewable energy that may be generated in the near future. This wastes renewable energy and is therefore suboptimal. Furthermore, we have already noted that when a battery is at a high state-of-charge, it can not accept charge at a high rate; if the battery is being charged by a genset, this will force the genset to operate at partial loading, which is inefficient and causes wear. These two considerations suggest that fully charging the batteries with the genset, except for purposes of equalization, is not optimal unless the energy that can be provided by renewable energy sources is very low.

Determining the actual optimal dispatch for a given system requires analysis beyond the scope of this document (see, for example, the method in [Barley et al., 1996]). However, some broad guidelines can be given.

6.5.1 Genset Turn-On

Three conditions should turn on the genset:

1) **Maximum depth-of-discharge**: When the battery approaches the state-of-charge that would cause the load to be disconnected in a comparable photovoltaic system (see Section 4), the genset should turn on. This protects the battery from harmful deep discharges.

2) **Equalization**: When equalization is required and the renewable energy sources are incapable of supplying sufficient power to do this, the genset should be turned on.

3) **Large Load**: Assume that surplus renewable energy has been used to fully charge the battery. A large load is turned on, and the net load-- the total load minus the power available from renewable sources-- is large. Should the battery be used to supply the net load? One might reason that since it has been charged by renewable energy, the energy in the battery is free. But this ignores the cost of battery wear caused by cycling. When the net load is large, a properly sized genset will be operating near full loading, and therefore be reasonably efficient. If the cost of the fuel that would be used is less than the cost of the battery wear that would be caused, then it will be cheaper to use the genset to power the load, regardless of the state-of-charge of the batteries. The critical net load above which the genset should be started can be estimated by comparing the battery cycling cost per unit of energy and the genset fuel costs per unit of energy [Barley et al., 1996], as shown below.

The battery cycling cost, c_{BW}, in \$/kWh can be estimated by

$$c_{BW} = \frac{c_{batt}}{E_{batt} . x_{typ} . l_{typ}}$$

where c_{batt} is the cost of the battery bank (\$),

E_{batt} is the energy capacity of the battery (kWh),

x_{typ} is the typical depth-of-discharge,

and l_{typ} is the number of cycles that can be expected at this typical depth-of-discharge. The typical depth-of-discharge will not be known without simulation; a conservative estimate can be found by using the maximum depth-of-discharge that the battery will be permitted to reach, and the cycle life at this depth-of-discharge.

While the battery cycling cost is constant regardless of the net load, P (in kW), the cost of operating the genset is a function of net load. Thus, the critical net load above which the genset should be started, P_{crit}, in kW, is found by solving for P when the battery cycling cost has been equated with the cost of operating the genset:

$$c_{BW} = \frac{c_F . F(P_{crit})}{P_{crit}}$$

where c_F is the cost of the genset fuel ($/litre),

and $F(P)$ is the genset fuel consumption as a function of load (litres/hour).

Generally, the genset fuel consumption curve can be assumed linear, and P_{crit} can be solved for explicitly:

$$P_{crit} = \frac{F_{100\%} - m.P_r}{\dfrac{c_{batt}}{c_F . E_{batt} . x_{typ} . l_{typ}} - m}$$

where $F_{100\%}$ is the genset fuel consumption at full load (litres/hour),

P_r is the rated power of the genset (kW),

and m is the slope of the fuel consumption curve (litres/kWh). This slope can be calculated from the fuel consumption at full load and any other point on the fuel consumption curve by:

$$m = \frac{F_{100\%} - F_{x\%}}{P_r - P_{x\%}}$$

where $F_{x\%}$ is the genset fuel consumption (litres/hour) at some loading, $P_{x\%}$ (in kW), other than 100%.

When batteries are very inexpensive compared with fuel, P_{crit} will exceed the rated genset power, or even be negative (it has an asymptote when c_{BW}/c_F is equal to m); then it never makes sense to start the generator if there is still energy stored in the batteries. If, on the other hand, fuel is inexpensive and batteries are costly, P_{crit} will approach zero. If this is the case, then the batteries do little to reduce the operating cost, and either they should be eliminated or peak shaving should be used.

It must be noted that this analysis ignores the cost of wear caused when starting the genset. If it is expected that the genset temperature will be fairly low, it is recommended that the value of P_{crit} be raised. Furthermore, since a start causes wear exceeding that resulting from one to four minutes of continuous operation, the genset should not be started for transients in the net load. If the net load contains many such transients, then it may be necessary to implement a delay, such that the net load must be greater than P_{crit} for several minutes before the genset is started. If this is not successful, and there is no other way to differentiate between transients and net loads that will be sustained, then this turn-on criterion should be ignored.

6.5.2 Genset Loading and Turn-off

Once the genset is on, two questions remain: How hard should the genset run, and for how long? There are various approaches. If the appropriate strategy has been chosen, the system will perform nearly optimally-- that is, even if the controller knew the future net load, operating costs could not be much reduced [Barley et al., 1996]. The ideal approach can not be identified without a detailed analysis, but the following guidelines can be helpful for systems having more than several hours of storage capacity.

If the genset was started in order to perform an **equalization charge**, then the genset should run either until equalization is complete or the renewable energy sources are able to fully supply the demand and charge the battery. The former criterion is simple to implement, avoids multiple genset starts, and will not waste that much fuel if equalization is relatively infrequent; often the latter criterion is ignored. The genset should run at full power until the battery can no longer accept charge at this rate; then the loading should be tapered according to the battery's ability to accept charge.

In one strategy, **load following**, the genset is run at the partial loading that is just sufficient to power the net load; genset power is not used to charge the batteries, except when the genset has a minimum permissible loading that exceeds the net load. If a large load started the genset, then the genset should run until the net load falls below P_{crit} . Otherwise, the genset should run until the net load is zero or negative (i.e., the renewable power sources alone can charge the batteries).

An alternate strategy is to run the genset at **full power**, using the power in excess of the net load to charge the batteries. If the genset was started due to the maximum depth-of-discharge being reached, then it should be shut off after a **minimum run time** has elapsed. The minimum run time should be about the time it takes for the genset to raise the battery state-of-charge by 10% to 20%, assuming average net loads; this strategy is applicable when the renewable penetration ratio-- i.e., the ratio of average power generated from renewables to average demand for power-- is greater than 0.5. A similar approach, and the one to be used if the genset was started due to a large load, is to shut off the generator when the battery exceeds a certain **minimum state-of-charge** and the load is below P_{crit}. If the state-of-charge exceeds this minimum threshold but the load is above P_{crit}, then the system can switch to load following; the genset is shut down when the net load falls below P_{crit}. When the penetration ratio is high (greater than one), the minimum state-of-charge should be about 10 to 20% of its allowable range (i.e., for a battery with a maximum depth-of-discharge of 50%, this would be a minimum state-of-charge of 55 to 60%). If the penetration is less than 0.25, the minimum state-of-charge should be 50 to 100 % of its allowable range; 100% is optimal for systems without renewable energy generation. With penetration between 0.25 and one, the minimum state-of-charge should vary in the range of 50% down to 20%. When cold starts are to be avoided, these minimum state-of-charge thresholds and minimum run times can be increased somewhat.

Which of these strategies should be used? Load following tends to make sense when the genset has not been oversized, fuel costs are low compared with battery wear costs, and/or the renewable generator penetration is very low or very high; full power dispatch strategies are advantageous when the genset is oversized, fuel costs are high compared with battery costs, and the penetration ratio of renewables is moderate. If the genset rated power exceeds the average demand by more than three times, load following will be attractive only when fuel costs are very low compared to battery wear costs. This results from the low efficiency of the genset when run at partial loading, which will occur frequently when the genset is greatly oversized. Low fuel costs and high battery costs favour load following, since the battery is being conserved at the expense of wasted fuel. As a very rough estimate, the ratio of battery to fuel costs is high when the delivered cost of the batteries, in \$ per kW, is more than 200 times the delivered cost of fuel, in \$ per litre[7].When the renewable energy penetration is less than 0.25, it is unlikely that the renewables will supply a large portion of the demand, so net loads will tend to be high; this permits the genset to run at reasonably high loadings during load following. When the penetration is greater than one, net loads are likely to be small, the battery state-of-charge likely to be high, and the system will not make use of the full power output of the genset; load following should be used. Of these factors, the extent to which the genset is oversized is paramount, and the relative cost of batteries and fuel and the penetration ratio are of lesser importance.

Some gensets have a minimum recommended loading which may exceed P_{crit} .When the genset is started due to a net load greater than P_{crit}, it may generate power exceeding the net load; eventually, the battery may become fully charged. At this point, diesel energy will be wasted; the solution is to raise P_{crit} to the minimum recommended loading whenever the battery is nearly fully charged. If this can not be accommodated, then either a dump load must be added (a reasonable approach if the above situation has a very low probability) or P_{crit} should be set to the minimum recommended loading at all times. A similar problem may arise if the full power/minimum state-of-charge strategy is used but the genset does not switch to the load following strategy when the load remains above P_{crit} but the minimum state-of-charge threshold has been reached.

When using the full power/minimum state-of-charge strategy, the state-of-charge is generally estimated on the basis of the current and temperature compensated battery voltage. Many controllers are capable of measuring the charge in and out of the battery; with these, the full power/minimum run time strategy should be modified, such that it becomes a full power/“minimum net charge in” strategy. The minimum net charge in should be equivalent to 10 to 15 % of the total useable battery capacity (that is, the total battery capacity multiplied by the maximum depth-of-discharge).

It may be necessary to seasonally or annually adjust the dispatch strategies. The penetration ratio of the renewables can change significantly from season to season; what is appropriate during summer for a photovoltaic hybrid system may not be appropriate during winter. If the rate of inflation for fuel costs differs from that for battery replacement, the strategy may need to be revised periodically.

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[7] This assumes batteries having an 80 % round trip efficiency with a lifetime of 800 equivalent full cycles; diesel generators are assumed. For batteries which cycle less well than this, the ratio should be compared with a figure less than 200.

INSTALLATION WARNINGS

- When installing charge controllers, be sure to follow the manufacturer's recommended sequence for connecting and wiring. Failure to follow these procedures exactly will result in damage to many models.
- Avoid reversing the polarity of the connections; this will often damage the controller.
- Charge controllers must never be installed in the same enclosure as batteries. Not only is a battery box a corrosive environment, but the hydrogen gas given off by the batteries can be ignited by the arcs created by a controller's contacts.
- Open the disconnect switches from the array and the battery bank before making or breaking connections at the charge controller. Potentially lethal amounts of current and voltage may be present in these wires.
- Position the controller as far from the battery as possible when making or breaking connections; this will diminish the probability of an arc igniting hydrogen gas generated by the battery.

7 INSTALLATION AND MAINTENANCE

7.1 Installation

Location and Placement

Charge controllers should be installed in locations which are sheltered from direct sunlight and which are appropriate for the enclosure type used. If installed on a module, the controller must be on the underside, and in a weatherproof housing. In most other cases, the controller should be situated indoors. Charge controllers should never be installed in a battery box or enclosure, since the arcing of the relay contacts can ignite the hydrogen which is vented from the battery. The location should be adequately vented; this is especially important for shunt-type controllers which can generate significant heat during normal operation. If the controller has a finned heat sink, the fins should be vertical in order to facilitate free convection.

Wiring

If the controller is installed indoors, the wire or cable used for connection can be of a type rated for dry, indoor locations. Conductors must be sized appropriately both from the standpoints of safety and efficiency. Since the charge controller is subjected to the full output of the array, its conductors must be rated for the total short circuit current of the array. This is somewhat higher than the operating current, and is determined by multiplying the short circuit current of one module times the largest number of modules connected in parallel, times the 1.3 safety factor. Besides sizing the conductor to electrical code requirements, larger gauge conductors will decrease wiring losses as shown in **Table 8**. The additional cost of increased conductor gauge should be traded off against the cost associated with the wiring losses. Most systems are sized to allow between 3% and 5% wiring loss between the array and the battery. If the controller includes a maximum power point tracker, it may be worth the expense to reduce these wiring losses to 1% to 2%.

Table 8: **Wire Sizes and Voltage Losses (current levels corresponding to shaded area are not recommended)**

Size		**Resistivity @ 25°C**	**Voltage drop (mV/m)**										
# AWG	mm^2	mohm/m	5A	7A	10A	15A	20A	30A	45A	65A	85A	120A	140A
1	42.4	0.415	2	3	4	6	8	12	19	27	35	50	58
2	33.6	0.522	3	4	5	8	10	16	23	34	44	63	
4	21.1	0.833	4	6	8	12	17	25	37	54	71		
6	13.3	1.32	7	9	13	20	26	40	59	86			
8	8.3	2.12	11	15	21	32	42	64	95				
10	5.27	3.35	17	23	34	50	67	101					
12	3.31	5.31	27	37	53	80	106						
14	2.08	8.43	42	59	84	126							
16	1.31	13.4	67	94	134								
18	0.821	21.4	107	150									
20	0.517	33.8	169										

In low voltage systems (less than 50 volts), a wire size of 3.3 mm^2 (12 AWG) or larger must be used. If multistrand wire is used, be careful to prevent strands of wire at one terminal from contacting other wires or terminals. Tinning multistrand wire with electrical solder is not recommended; rather, use crimp-on terminals. Use ring rather than spade terminals unless disconnection is expected to occur more than twice a year.

It is important to maintain correct wire insulation colours; conventions for these vary from country to country. If the correct insulation colour is not available, use appropriately coloured tape to code the wire.

Fusing and Disconnects

Fuses, disconnects and circuit breakers (fuse plus disconnect) are as important in a photovoltaic system as they are in any other electrical system. They should be used on the array and the battery bank, as they are both sources of electric power. All components must be rated and certified for DC applications since the contacts of many AC circuit breakers will fail as a result of the arcing associated with interrupting a DC current. In smaller systems, clip-in fuses can be used both for fusing and for disconnection. Time delay or "slow blow" fuses can be used to accommodate the current surges of starting motors, but the fuses used must be recognized for DC with DC ratings. As with AC systems, fuses, circuit breakers and switches in photovoltaic systems must not be in the grounded conductors. In bipolar systems, where the center tap is grounded, fuses and disconnects are required in both positive and negative conductors.

It is important to account for the voltage drop across the fuse when determining the appropriate voltage regulation setpoint, especially in systems which do not use voltage sense wires. Small clip-in fuses (e.g. 20A) can cause voltage drops of 10 mV/A.

Temperature Compensation Probe

If the charge controller includes a temperature compensation probe, secure it in one of three ways:

1) Carve a hollow out of a piece of rigid foam insulation the same size as the probe, with a channel out of the hollow for the probe wire. Tuck the probe in the hollow, and tape the insulation to the side of the battery. Wrap the tape all the way around the battery for a better grip. Install the probe in a location sheltered from cold air and direct sunlight. If the probe wiring needs to be extended, the connections must be soldered.

2) Use thermally conducting, electrically insulating binder to attach the probe directly to the case of the battery.

3) Bolt the probe directly on the negative terminal of the battery. This should be done only when recommended by the controller manufacturer.

4) If a probe is not available, many controllers can be operated with a jumper wire or a specific resistor until a probe can be obtained. Consult the manufacturer's information for details.

Setpoint Adjustments

If the controller has adjustable charging and discharging setpoints, apply the optimal settings for the system based on Section 2.2. When a system has a non-adjustable charge controller with inappropriate settings, consider installing a different one, with charge and discharge setpoints more appropriate for the battery type and loads used in the system.

Check the battery voltage or specific gravity for a few days following an adjustment, to confirm that the controller is effectively protecting the batteries from excessive charging and discharging. If this inspection is not practical, use a portable adjustable power supply for accurate adjustment and verification of the controller.

Synchronization of Charge Controllers

Some controllers, such as series-relay types, may operate incorrectly when they are first energized due to internal timers which are out of synchronization. Most of these will reset themselves after either one night, or a full 24-hour period. However, it is also possible that the correct connection sequence was not followed, therefore if the site cannot be visited the next day to confirm self-resetting, some controllers can be manually reset by disconnecting and reconnecting the unit. Consult the manufacturer's information for details.

Environmental Conditions

The charge controller should be clean. It should be securely mounted in a dry, protected area. It should not be subjected to unreasonable temperature extremes.

7.2 Maintenance Procedures

Check to make sure the power is off at the charge controller. If it is necessary to disconnect live wires, be sure to follow the disconnection sequence recommended by the charge controller manufacturer. When the battery is disconnected, some charge controllers will permit the PV array to set the system voltage; since the resulting elevated voltages can destroy certain loads, this possibility should be investigated before the battery is disconnected.

Connections and Wires

Check all terminals and wires for loose, broken, corroded, or burnt connections or components. Make sure there are no loose strands of multistrand wire. These can short out on other terminals or on loose strands from other wires.

Temperature Compensation Probe

Check the terminal connections of the temperature compensation probe, if the charge controller is equipped with one. If the probe wiring needs to be extended, the connections must be soldered and the extension wire must be the same as that of the thermocouple type, not the plain copper wires. Be sure the probe is in good thermal contact with the side of one or more batteries. The probe must not be immersed in the electrolyte. The charge controller manufacturer may supply a chart showing the resistance or voltage through the sensor in the temperature compensation probe. If this is available, check the sensor for proper calibration.

8 TROUBLE-SHOOTING

Many charge controller problems are caused by loose connections, blown fuses, or switches in the wrong position. After verifying these points, remove the charge controller cover and look for dirt, corrosion, insects, or other problems at the relay contacts. Look for evidence of temperature extremes or high humidity in the area where the charge controller is installed.

Many charge controller problems result from either oversized loads or loads which require high surge of current. Load related problems range from blown fuses to low battery voltages and improperly operating loads. Measure the current draw of the loads, both operating and starting, and compare with the design load and the charge controller nameplate amperage rating.

Compare the readings of any charge controller meters to those measured by portable meters. Use these measurements to confirm that LEDs and LCD readouts are functioning correctly. Typically, high quality portable meters are more accurate than those used in the controller. It may be possible to recalibrate the system meters to agree with the portable meters. Make sure the voltage windows of the charge controller and the batteries are compatible.

After checking all these points, consult the troubleshooting table which follows.

TROUBLE-SHOOTING TABLE

SYMPTOM	CAUSE	RESULT	ACTION
Battery voltage below Voltage Regulation Reconnect setpoint but controller not charging batteries	Faulty charge resumption function in controller	Excessive battery discharge	Repair, readjust, or replace controller
Battery voltage just below Voltage Regulation Reconnect setpoint, but controller not charging batteries	Faulty or poorly positioned temperature probe	Charge controller thinks batteries are cooler than their actual temperature	Repair, replace or reposition probe
	Operating point of PV module is far right of I-V curve knee due to high module operating temperature (very hot, sunny summer days)	Under charging of batteries	PV module may have to be changed so that the VR is close to the I-V curve knee under hot conditions
Battery voltage below low voltage disconnect setting	Faulty low voltage disconnect function in charge controller	Excessive battery discharge	Repair or replace charge controller
	One battery cell faulty	Battery capacity limited	Check cells and replace
Battery voltage loss overnight even when no loads are drawing current	Faulty blocking diode, no diode, or faulty charge controller	Reverse current flow at night discharging batteries	Replace or add diode, or repair or replace series relay charge controller
	Old or faulty batteries	Batteries self-discharging	Replace batteries
Battery voltage not increasing even when no loads are on and the system is charging	Faulty charge controller	No power from array going into batteries	Repair or replace charge controller
Battery voltage over Voltage Regulation setpoint	Faulty charge controller	Shortened battery life, possible damage to loads	Repair or replace charge controller and possibly batteries
	Controller always in full charge, never in float charge	Shortened battery life, possible damage to loads	Repair or replace charge controller and possibly batteries
Battery experiencing high water loss	Poorly configured charge controller	Shortened battery life, possible damage to loads and batteries	Adjust setpoint, repair or replace charge controller and possibly batteries
	Controller always in full charge, never in float charge	Shortened battery life, possible damage to loads	Repair or replace charge controller and possibly batteries
Battery voltage just above Voltage Regulation setpoint, but controller still charging batteries	Faulty or poorly positioned temperature probe or poor connection at controller “battery sense” terminals	Charge controller thinks batteries are warmer than their actual temperature	Repair, replace or reposition temperature probe or change charge controller

SYMPTOM	CAUSE	RESULT	ACTION
Buzzing relays	Too few batteries in series or low battery voltage	Low voltage across relays	Reconfigure, add or replace batteries
	Loose or corroded battery connections	High voltage drop	Repair or replace cables
Erratic controller operation and/or loads being disconnected improperly	Timer not synchronized with actual time of day	Controller turns on and off at incorrect times	Either wait until automatic reset next day, or disconnect array, wait 10 seconds, and reconnect array. Replace controller if this does not resynchronize controller.
	Electrical “noise” (EMI) from inverter	Rapid on and off cycling	Connect inverter directly to batteries, put filters on load
	Low battery voltage	Batteries may need repair or replacement	Repair or replace batteries
	Faulty or poorly positioned temperature probe or poor connection at battery sense terminals	Charge controller thinks batteries are warmer or cooler than their actual temperature	Repair, reposition or replace temperature probe or change charge controller
	High surge from load	Battery voltage drops during surge	Use larger wire to load, or add batteries in parallel
	Faulty charge controller, possibly from lightning damage	Loads disconnected improperly, other erratic operation	Repair or replace charge controller and check system grounding
	Adjustable low voltage disconnect set incorrectly	Loads disconnected improperly	Reset Low Voltage Disconnect setpoint
	Controller load switch in wrong position	Loads never disconnect	Reset switch to correct position
Fuse to PV array blows	Array short circuited with batteries still connected (possibly faulty blocking diode)	Too much current through charge controller	Test diode and replace controller if required
	Current output of array too high for charge controller	Too much current through charge controller	Replace charge controller with one with higher rating
Fuse to load blows	Short circuit in load	Unlimited current	Repair short circuit or replace load
	Current draw of load too high for charge controller	Too much current through charge controller	Reduce load size or increase charge controller size
	Surge current draw of load too high for charge controller	Too much current through charge controller	Reduce load size or increase charge controller size
“Charging” at night	Normal operation for some charge controllers for up to two hours after nightfall	No appreciable energy loss	Check system later in the evening
	Timer not synchronized with actual time of day	Controller turns on and off at incorrect times	Either wait until automatic reset next day, or disconnect array, wait 10 seconds, and reconnect

9 RECOMMENDED TEST AND QUALIFICATION PROCEDURES

9.1 Introduction

Under standard operating conditions, most controllers perform according to their specification. When used in real conditions, however, they can fail or malfunction in a number of ways; furthermore, if a controller's specified operating characteristics are inappropriate, it can cause problems in the operation of the system. The controller must be tested extensively in order to ensure that it functions adequately under all conditions it is expected to encounter. In the past, it has usually been the manufacturer's responsibility to do this testing, and the consumer's responsibility to demand that this testing be done. Increasingly, national and international standards requiring this testing are being applied to charge controllers.

9.2 Controller Testing

9.2.1 Basic Function

At a minimum, the controller should function as it is specified: it should regulate charging when the battery is fully charged and, if so equipped, disconnect the load when the battery is in danger of being overdischarged. Tests for basic functionality principally involve verifying all setpoints over the entire range of operating temperatures. They may also include measurements of the voltage drop across the controller and the quiescent (standby) current draw. Most controllers pass such tests; it is not generally worthwhile for the user to test the controller for basic functionality, except when the application is extremely important or a large number of controllers will be used. Many manufacturers test a sample of their controllers over a range of temperatures, and test each of their units for basic operation at room temperature.

9.2.2 Safety and Reliability

Each model of controller should be subjected to a battery of safety and reliability tests. These tests, which tend to be time-consuming and require special test equipment, should be done by the manufacturer. The controller design should be tested for:

Electromagnetic Interference (EMI)

The controller should function properly when placed within a radiated electromagnetic field; additionally, the controller should not emit significant electromagnetic fields, which can disrupt sensitive electronic loads, such as telecommunications equipment.

Reverse Polarity Connections

A number of different wires must be connected to a charge controller, and the possibility exists that these will be connected improperly. For example, it is easy to connect the positive lead of the array to the negative lead of the controller. Many charge controllers have been damaged in this way. A large number of the more probable combinations of improperly wired connections should be tested to ensure that these do not cause fires or damage the controller.

Overvoltage Protection

When lightning strikes near a photovoltaic system, a high transient voltage may be seen at the terminals of the controller. The controller must be able to withstand this overvoltage without damage. These conditions can be simulated in the laboratory, permitting tests for overvoltage protection.

Thermal Cycling

Most charge controllers will be situated out-of-doors, with the result that the temperature of the controller will fluctuate with the ambient air temperature. These fluctuations fatigue components within the controller, especially when the controller is potted (encased in protective resin). Furthermore, high temperatures cause accelerated rates of corrosion. A sample of each type of controller should be cycled repeatedly over its specified range of operating temperatures and periodically inspected for failure. This testing should continue for an extended period of time (ideally, for years) and include a large number of thermal cycles.

Thermal Runaway

With some controller designs there exists the danger that under certain conditions the controller will generate sufficient heat that the temperature of the controller will rise until the controller is damaged. “Thermal runaway” tends to be a concern when the controller is operating in still air at the maximum specified ambient temperature and the array is furnishing the maximum rated charge current for the controller. In shunt and constant voltage-type controllers, thermal runaway is most likely to occur during regulation.

Stability

Especially with more advanced controllers such as those employing pulse width modulation, it is important that the output from the controller to the battery remains within its specified voltage and current levels at all times. If problems with stability are to arise, they will probably do so when the battery is fully charged, clouds cause the charging current to change rapidly, loads vary rapidly, or at sunrise. These conditions should be simulated and the correct operation of the controller verified.

Start-up at Cold Temperatures

The controller must be able to function correctly with feeble currents at low temperatures, especially following a period of several hours without charge current; this simulates start-up at sunrise on a cold day.

9.2.3 Operation within a System

Many reliable, safe controllers fail to fully charge certain batteries, even when operating exactly as specified. This problem arises when the controller is ill-suited to the system, principally the battery. Whenever possible, the suitability of the controller to the system should be verified. At present, the only way to do this is to test the battery in conjunction with either the charge controller itself or a programmable charger that can simulate the operation of the charge controller very closely. Generally a programmable current source is used to simulate the photovoltaic array; this permits testing of the systems under varying conditions of insolation. If possible, the test should involve cycling the battery between partial states-of-charge, then permitting the controller to recharge the battery. The initial cycling will simulate conditions leading to stratification. The controller should be able to fully recharge and destratify the battery. This can be tested by measuring the capacity at the end of the test, and comparing the capacity to that available following a full charge using standard charging methods. For these tests the charge and discharge rates should be representative of those that will occur in the photovoltaic system; thus, this testing is very time consuming.

9.3 Safety Standards

Presently, very few safety standards apply specifically to charge controllers for photovoltaic systems, although there is mention of controllers in some national electrical codes (for example, in the United States National Electrical Code Section 690). When charge controllers are used for residential systems, they must comply with standards applicable to power conditioning devices used in residential buildings. These standards include UL 1741 and IEC 364. These standards apply to all residential power conditioning units, and therefore contain little of special relevance to PV charge controllers.

9.4 Performance Standards

There are no standards for the validation of the correct operation of a charge controller within a photovoltaic system. This is a very real need, and in response to this need several standards are being prepared. Internationally, the Global Approval Programme for Photovoltaics (PV GAP) is working on performance standards[8] for photovoltaic systems, including charge controllers. In addition, there are efforts underway in other organizations, including TUV Rheinland[9] and the IEEE Standards Coordinating Committee 21[10].

For controller performance with respect to overvoltage protection and electromagnetic radiation, existing standards for other electrical devices are applicable. In particular, for EMI, the European standards EN 50081-1, EN 50081-2, EN 50082-1, EN 55011, and EN 55014 should be consulted. The IEC 801-2, IEC 801-3, and IEC 801- 4 are also applicable. For electrostatic discharge, EN 61000-4-2 is applicable.

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[8] Work coordinated by H. Ossenbrink, Joint Research Centre, Ispra, Italy.

[9] Work coordinated by W. Wiesner, TUV Rheinland, Koeln, Germany.

[10] Work coordinated by R. Swamy, Florida Solar Energy Center, Cocoa, Florida.

GLOSSARY OF TERMS

Absorbed Glass Mat (AGM) Battery: A sealed battery in which the electrolyte is largely immobilized by absorption into a glass mat within the battery.

Autonomy: A measure of the size of battery bank in comparison with the load, the autonomy is the capacity of the battery divided by the average load. It is usually specified in days.

Battery: Two or more electrochemical storage cells electrically interconnected in an appropriate series or parallel arrangement to provide the required operating voltage and current levels. Under common usage, the term battery also applies to a single cell if it constitutes the entire electrochemical storage system.

Battery Life: The period during which a cell or battery is capable of operating above a specified capacity or efficiency performance level. With lead-acid batteries, end-of-life is generally taken as the point in time when a fully-charged cell can only deliver 80% of its rated capacity. Beyond this state of aging, deterioration and loss of capacity begins to accelerate rapidly. Life may be measured in cycles and/or years, depending on the type of service for which the cell or battery is intended.

Boost Charge: The elevated VR setpoint initially used by two stage interrupting charge controllers. Once the boost charge setpoint has been reached, the VR setpoint reverts to its regular level.

Capacity (C): Generally, the total number of ampere-hours that can be withdrawn from a fully charged cell or battery.

Charging: Conversion of electrical energy into chemical potential energy within a cell by the passage of a direct current in the direction opposite to that of discharge.

Constant Voltage Charging: A method of charge regulation in which the current is tapered in order to maintain the battery voltage constant. Also known as constant potential charging.

Cutoff Voltage: The cell or battery voltage at which discharge should be terminated. Cutoff voltage (also called “final voltage”) is specified by the battery manufacturer and is generally a function of discharge rate. Discharges beyond the specified cutoff voltage usually result in a rapid decline in cell voltage and energy output, may permanently damage the cell, and may void the manufacturer's warranty.

Cycle: One discharge-charge sequence to a specified depth-of-discharge.

Cycle Life: The number of cycles, to a specified depth-of-discharge, that a cell or battery can undergo before failing to meet its specified capacity or efficiency performance criteria.

Deep Discharge: Discharge of a battery to a low state-of-charge (typically below 50 %).

Discharge: The process of withdrawing current from a cell or battery by the conversion of chemical energy into electrical energy.

Electrolyte: The medium which provides the ion transport mechanism between the positive and negative electrodes of a cell. In some cells, such as lead-acid type, the electrolyte may also participate directly in electrochemical charge/discharge reactions.

Equalization: The process of restoring all cells in a battery to an equal state-of-charge. For lead-acid batteries, this is a charging process designed to bring all cells to 100 percent state-of-charge.

Equalizing Charge: A continuation of normal battery charging, at a voltage which is slightly higher than the normal end-of-charge voltage, in order to provide cell equalization within a battery.

Float Charging: Holding a fully charged battery on a constant voltage charge at a voltage not much above the cell voltage in order to ensure that it stays fully charged.

Float Service: A duty cycle characterized by long periods of standby operation, at full charge and constant voltage, with only occasional discharge/charge sequences.

Flooded Battery: A battery which contains liquid electrolyte that is free to circulate within the battery and is not immobilized in an absorbent glass mat or gel.

Gassing: The evolution of hydrogen and oxygen gas from one or more of the electrodes in a cell. Gassing commonly results from the electrolysis of water in the electrolyte during charging.

Gelled Electrolyte Battery: A sealed battery in which the electrolyte is immobilized in a gel.

Immobilized Electrolyte Battery: A sealed battery in which the electrolyte is not free to circulate due to it being immobilized in a gel or an absorbent glass mat.

Interrupting Controller: A charge controller which regulates charging by interrupting the flow of current to the battery whenever the battery voltage reaches the VR setpoint. Current flow is reestablished when the battery voltage falls to the VRR setpoint. Also known as an "on/off" controller.

Low Voltage Disconnect setpoint (LVD): For controllers which regulate battery discharge, the LVD is the end-of-discharge voltage setpoint; the controller disconnects the load at this voltage, preventing further discharge.

Low Voltage Reconnect setpoint (LVR): After a LVD has occurred and the load has been disconnected from the battery, the LVR setpoint is the voltage threshold which the battery must attain prior to the load being reconnected.

Nominal Operating Voltage: The average terminal voltage of a cell or battery discharging at a specified rate and at a specified temperature.

On/off Controller: A charge controller which regulates charging by interrupting the flow of current to the battery whenever the battery voltage reaches the VR setpoint. Current flow is reestablished when the battery voltage falls to the VRR setpoint. Also known as an "interrupting" controller.

Open Circuit Voltage: The terminal voltage of a cell or battery at a specified state-of-charge and temperature under no-load conditions.

Overcharge: The forcing of current through a cell after all of the active material has been converted to the charged state. In other words, charging continued after 100 percent state-of-charge is achieved. Overcharging does not increase the energy stored in a cell and usually results in gassing and/or excessive heat generation, both of which reduce battery life.

Pulse-Width Modulation (PWM) Controller: This method uses solid state switches to apply pulses of current with a varying duty cycle at relatively high frequency (e.g., 300 Hz) such that the battery receives a constant voltage charge from the array.

Rate: The flow of current into or out of a battery, expressed in terms of the number of hours it would take the battery to be brought from 100% SOC to 0% SOC by a discharge current of the same magnitude. For instance, if the 20 hour capacity of a battery is 100 AmpHours and the battery is being charged with 5 Amps of current, the battery is being charged at the 20 hour rate, usually written as “C/20” and pronounced “C on 20”.

Sealed Battery: A battery which is sealed at the end of its construction; electrolyte can not be added. Also known as a “maintenance-free” battery.

Self-discharge: The gradual discharge of an open-circuited cell due to electrochemical reactions within the cell.

Series Controller: As a battery approaches full charge, a series controller will open-circuit the PV array to reduce the charging current applied to the battery.

Series Interrupting Controller: This method terminates charging at the VR setpoint with an in-series element which open-circuits the PV array. As with the shunt interrupting on/off controllers, charging is then resumed once battery voltage falls below the VRR setpoint.

Series Linear Controller: This method applies a constant voltage to the battery as it approaches the full charge VR setpoint by using a series control element which acts like a variable resistor. This element dissipates the balance of the power that is not used to charge the battery.

Shunt Controller: As a battery approaches full charge, a shunt controller will short-circuit the PV array to reduce the charging current applied to the battery.

Shunt Interrupting Controller (On/Off): This method diverts array energy to a parallel (or shunt) path when the battery reaches the full charge VR setpoint. Charging is then resumed once battery voltage falls below the VRR setpoint.

Shunt Linear Controller: This method uses a control element to maintain the battery at the VR setpoint as it approaches full charge. By shunting power away from the battery in a linear manner, this provides a constant voltage charge to the battery.

State-of-charge (SOC): The available capacity in a cell or battery expressed as a percentage of rated capacity. For example, if 25 ampere-hours have been removed from a fully charged 100 ampere-hour cell, the SOC is 75%.

Stratification: The existence of a vertical density gradient within the electrolyte of a flooded lead-acid battery. During charge, high density sulfuric acid is generated at the plates and sinks to the bottom of the battery.

Sub-Array Switching Controller: This method is similar to the series interrupting circuit, except that rather than open-circuiting the entire array, sub-arrays are gradually switched out to decrease the charging current as the battery nears its end of charge.

Sulfation: The formation of lead-sulfate crystals on the plates of a lead-acid battery. Commonly used to indicate the large crystals which form in partially discharged cells. These crystals are more difficult to reduce by the charging current than are the smaller crystals that result from normal and self-discharge reactions. Sulfation can be caused by leaving the battery in a discharged state for long periods of time.

Two Stage Controller: A controller in which the end-of-charge regulation occurs at two voltages; initially at a higher boost or equalization voltage, then at the regular VR setpoint. Alternately, some two stage controllers perform regulation at two current levels: initially the full output of the PV array is used, then when the VR setpoint has been reached, the current is reduced to a much lower "trickle" charge level, which finishes the charge.

Valve-regulated lead-acid battery (VRLA battery): A sealed battery; the name comes from the existence of vents in the battery that normally remain closed but will open to prevent the pressure within the battery from reaching dangerous levels.

Vented Battery: A battery in which vents permit the addition of electrolyte to the cells.

Voltage Regulation setpoint (VR): The VR setpoint is the end-of-charge voltage for the battery. The controller will either end charging when the battery reaches this voltage, or will maintain the battery at this *float* voltage using a method of constant voltage charging.

Voltage Regulation Reconnect setpoint (VRR): For On/Off type controllers, which interrupt battery charging when the VR setpoint is reached, the VRR value specifies at which point the charging will resume as the battery voltage drops. This term does not apply to controllers which use a constant voltage charging algorithm.

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