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PERFORMANCE OF BATTERY CHARGE CONTROLLERS:**FIRST YEAR TEST REPORT**

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The results of the first year of an evaluation of charge controllers for stand-alone photovoltaic (PV) systems are presented. The objectives of the test program are to positively influence the development of battery charge controllers for stand-alone PV applications and to develop design and application criteria that will improve PV system reliability and battery performance. Future goals are to expand the evaluation program to include various battery technologies and controller algorithms. Also, the information is being communicated to manufacturers to aid in the design of more effective and reliable charge controllers for PV systems.

Eight different models of small (nominal 10 amp) charge controllers are being subjected to a comprehensive evaluation. These evaluations include operational tests in identical stand-alone PV systems and environmental and electrical cycling tests. Selected custom tests are also performed on the controllers to determine the response to transients, installation requirements and system design compatibilities. Data presented in this paper include measured electrical characteristics of the controllers, temperature effects on set points, and operational performance in PV systems both in the lab and in the field. A comparison is presented for four different charge controller algorithms which include array-shunt, series-interrupting, series-linear constant-voltage and series-linear-multistep constant-current.

charge controllers with various algorithms and options under a variety of simulated and actual operating conditions experienced in PV systems. This report describes the scope of the evaluations and first year performance results for the eight different models of small (nominal 10 amp PV current) charge controllers under test. A description of the evaluation program and preliminary results of the testing were reported at the 21st IEEE PVSC, 1990 (1).

The controllers are being subjected to comprehensive tests including electrical characterizations at selected temperature extremes and operating conditions. After electrical characterizations, the charge controllers are divided into concurrent evaluation paths. One path consists of side-by-side operational systems tests in which the charge controllers are installed in identical stand-alone PV systems. The other path consists of continuous environmental and electrical cycling in which the controllers are subjected to programmed electrical inputs, temperatures, and relative humidities. Re-characterizations of all controllers are performed on a periodic basis to detect changes in electrical performance. In addition, selected custom tests are performed on identical models to determine response to transients, installation issues and system compatibilities (1).

BACKGROUND

Sandia National Laboratories (Sandia) and the Florida Solar Energy Center (FSEC) are currently in the second year of an extensive program to evaluate charge controllers for stand-alone photovoltaic systems. The objective of the program is to test

INTRODUCTION TO CHARGE CONTROLLERS

The primary function of a charge controller in a stand-alone PV system is to protect the battery from overcharge and overdischarge. Any system that has unpredictable loads, user intervention, optimized or undersized battery storage (to minimize initial cost), or any characteristics that would allow excessive battery overcharging or overdischarging requires a

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charge controller and/or low-voltage load disconnect, or the result will be a shortened battery lifetime and decreased load availability.

Systems with small, predictable, and continuous loads may be designed to operate without a battery charge controller. If system designs incorporate oversized battery storage and battery charging currents are limited to safe finishing charge rates (C/50 flooded or C/100 sealed) at an appropriate voltage for the battery technology, a charge controller may not be required in the PV system (2,3,4,5).

Proper operation of a charge controller should prevent overcharge or overdischarge of a battery regardless of the system sizing/design and seasonal changes in the load profile and operating temperatures. The algorithm or control strategy of a battery charge controller determines the effectiveness of battery charging and PV array utilization, and ultimately the ability of the system to meet the load demands. Additional features such as temperature compensation, alarms, and special algorithms can enhance the ability of a charge controller to maintain the health, maximize capacity, and extend the lifetime of a battery.

Basics of Charge Controller Theory

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

Regulation set point (VR): The maximum voltage that a controller allows the battery to reach. At this point a controller will either discontinue battery charging or begin to regulate the amount of current delivered to the battery. Proper selection of this set point depends on the specific battery chemistry and operating temperature. Temperature compensation of the VR set point is often incorporated in controller design, and is particularly desirable if battery temperature ranges exceed $\pm 5^\circ\text{C}$ at ambient temperatures (25°C). For flooded lead-acid batteries, a widely accepted temperature compensation coefficient is $-5\text{ mV}/^\circ\text{C}/\text{cell}$ (3). If the electrolyte concentration has been adjusted for local ambient temperature (increase in specific gravity for cold environments, decrease in specific gravity for warm environments) and temperature variation of the batteries is minimal, compensation may not be as critical.

Regulation hysteresis (VRH): The voltage span or difference between the VR set point and the voltage when the

full array current is reapplied. The greater this voltage span, the longer the array current is interrupted from charging the battery. If the VRH is too small, then the control element will oscillate, inducing noise and possibly harming the switching element. The VRH is an important factor in determining the charging effectiveness of a controller.

Low voltage disconnect (LVD): The voltage at which the load is disconnected from the battery to prevent overdischarge. The LVD defines the actual allowable maximum depth-of-discharge and available capacity of the battery. The available capacity must be carefully estimated in the system design and sizing process. Typically, the LVD does not need to be temperature compensated unless the batteries operate below 0°C on a frequent basis. The proper LVD set point will maintain good battery health while providing the maximum available battery capacity to the system.

Low voltage disconnect hysteresis (LVDH): The voltage span or difference between the LVD set point and the voltage at which the load is reconnected to the battery. If the LVDH is too small, the load may cycle on and off rapidly at low battery state-of-charge (SOC), possibly damaging the load and/or controller. If the LVDH is too large, the load may remain off for extended periods until the array fully recharges the battery. With a large LVDH, battery health may be improved due to reduced battery cycling, but this will reduce load availability. The proper LVDH selection will depend on the battery chemistry, battery capacity, and PV and load currents.

CHARGE CONTROLLER ALGORITHMS

Two basic methods exist for controlling or regulating the charging of a battery from a PV module or array - series and shunt regulation. While both of these methods can be effectively used, each method may incorporate a number of variations that alter basic performance and applicability. Following are descriptions of the two basic methods and variations of these methods.

Shunt Controller

A shunt controller regulates the charging of a battery by interrupting the PV current by short-circuiting the array. A blocking diode is required in series between the battery and the switching element to keep the battery from being shorted when the array is shunted. This controller typically requires a large heat sink to dissipate power. Shunt type controllers are usually designed for applications with PV currents less than 20 amps due to high-current switching limitations.

Shunt-linear: This algorithm maintains the battery at a fixed voltage by using a control element in parallel with the battery. This control element turns on when the VR set point is reached, shunting power away from the battery in a linear method (not on/off), maintaining a constant voltage at the battery. This relatively simple controller design utilizes a Zener power diode which is the limiting factor in cost and power ratings.

Fig. 1. Daily charge profile for a shunt-interrupting controller.

Fig. 2. Daily charge profile for series-interrupting controller.

Shunt-interrupting: This algorithm terminates battery charging when the VR set point is reached by short-circuiting the PV array. This algorithm has been referred to as "pulse charging" due to the pulsing effect when reaching the finishing charge state. This should not be confused with Pulse Width Modulation (PWM). Figure 1 illustrates a typical daily charge profile for a shunt-interrupting controller in a system with a 24-hour continuous load.

Series Controller

There are several variations to this type of controller, all of which use some type of control element in series between the array and the battery.

Series-interrupting: This algorithm terminates battery charging at the VR set point by open-circuiting the PV array. A blocking diode may or may not be required, depending on the switching element design. Some series controllers may divert the array power to a secondary load. Figure 2 illustrates a typical daily charge profile for a series-interrupting controller in a system with a 24-hour continuous load.

Series-interrupting, 2-step, constant current: Similar to the series-interrupting, however when the VR set point is reached, instead of totally interrupting the array current, a limited, constant current remains applied to the battery. It is expected that this will allow for an increased charging effectiveness of the basic series-interrupting algorithm.

Fig. 3. Daily charge profile for a series-linear, constant-voltage controller.

Series-interrupting, 2-step, dual set point: Similar to the series-interrupting, however there are two VR set points. A higher set point is only used during the initial charge each morning. The controller then regulates at a lower VR set point for subsequent cycles for the rest of the day. This allows a daily gassing period or equalization of the battery. It is anticipated that this will allow for an increased charging effectiveness of the series-interrupting algorithm.

Series-interrupting, Pulse Width Modulated (PWM): This algorithm uses a series element which is switched on/off at a variable frequency with a variable duty cycle to maintain the battery at the VR set point. Similar to the series-linear, constant-

voltage algorithm in function, power dissipation is reduced with the series-interrupting PWM algorithm. A typical daily charge profile for a series-interrupting PWM controller is identical to Fig. 3, with the exception of added noise in the system.

Series-linear, constant-voltage: This algorithm maintains the battery voltage at the regulation set point (VR). The series control element acts like a variable resistor to maintain the battery at the VR set point. The series element dissipates the balance of the power that is not used to charge the battery. The current is inherently controlled by the series element and the voltage drop across it. This is the recommended charge algorithm for sealed, valve-regulated batteries. Figure 3 illustrates the typical daily charge profile of a series-linear, constant-voltage controller in a system with a 24-hour continuous load.

Fig. 4. Daily charge profile for series-linear, constant-current-modified controller.

Series-linear, constant-current-modified (EMAC): The Energy Management and Control (EMAC) is a charge controller being developed at Sandia. The controller uses a multi-step charging algorithm with several advanced features to enhance the amount of charge that will be accepted by the battery. This technology will be available to the industry when development is completed.

The EMAC algorithm has several features and steps during the daily charging profile. The voltage regulation set point is adjusted for the specific battery type being used. The regulation set point is temperature compensated at $-5 \text{ mV}/^{\circ}\text{C}/\text{cell}$ and also compensated for the rate at which the battery is being charged. This allows the battery to receive a full charge, negating the effects of internal resistance which produces an artificially high battery voltage at the terminals during charging. When this regulation set point is reached the controller goes to a preset constant current charge rate to facilitate controlled charging.

The battery voltage is then clamped to a specific voltage level determined by the battery chemistry used. The charge rate will return to constant current linearly as the battery voltage decreases. All of these features are selectable with a "personality module," allowing the units to be easily factory configured or modified in the field. Figure 4 illustrates a typical daily charge profile for the series-linear, constant-current-modified controller in a system with a 24-hour continuous load.

EVALUATION RESULTS

Systems Tests

Laboratory controlled systems tests are being performed at the two separate facilities along with evaluations of systems in the field to corroborate the data. Specific trends in performance can be attributed to regulation algorithms, set points, hysteresis values, and temperature compensation. Although in different climates, identical trends have been seen at both the FSEC and Sandia evaluation sites. Following are discussions on specific issues related to the systems tests.

Condition of batteries. A key indicator of the performance of battery charge controllers is the general condition and maintenance requirements of the batteries. Although there were no catastrophic battery failures at Sandia or FSEC during the system tests, measured battery capacities ranged from 30 to 103 percent of initial measured capacities after one year of testing at FSEC. Several batteries appeared to be sulfated after the first year, with indications of similar results after nine months of testing at Sandia. Some battery capacity recovery was observed for the sulfated batteries after repeated controlled charge-discharge cycles at FSEC.

Table 1 defines the algorithms, set points, hysteresis, and options of the equipment tested at Sandia (6). Figure 5 shows the battery capacity at the start of the testing at Sandia with capacity tests performed at 3, 4½, 6 and 9 months. The initial drop in capacity at 3 months was primarily due to low insolation and cold temperatures during the winter (Sandia tests began November 1990). This 3 month period magnified any problems an algorithm may have had in maintaining a high battery SOC. The effects of temperature compensation, regulation set points and hysteresis can be observed here.

Figure 6 shows the history of battery water added for each of the systems at Sandia over the same nine month period. The constant-voltage controller in system #4 experienced the most water loss until the summer months, followed by the PWM controller in system #3. As battery temperatures increased in the summer months, typically 100-120°F, systems without temperature compensation experienced a significant increase in water loss.

Table 1. Description of controllers at Sandia (25 °C).

System #	VR	VRH	LVD	LVDH	Temperature Compensation	Algorithm Description
1	14.35	1.33	11.00	1.48	No	Series-Interrupting
2	14.54	1.09	11.89	1.68	-4mV/C/Cell	Shunt-Interrupting
3	14.40	N/A	N/A	N/A	No	Series-Interrupt PWM
4	14.40	<1.00	11.80	1.40	-3mV/C/Cell	Series-Constant Volt
5	14.35	0.91	11.48	1.67	No	Shunt-Interrupting
6	14.40	1.74	11.80	1.40	-5mV/C/Cell	Shunt-Interrupting
7	14.35	1.20	N/A	N/A	-3.8mV/C/Cell	Shunt-Interrupting
8	14.40	1.60	11.80	2.80	-3mV/C/Cell	Series-Multi-Step Constant Current

Notes: System 8 has constant current at 2 Amperes in Regulation mode with a 15.0 volt maximum battery voltage limit.

Sandia Hardware Description

Both under and overcharge situations can be detrimental to the lifetime of the battery. As shown in Fig. 5, system #1 is suffering from severe undercharging and systems #5,6 and 7 are somewhat undercharged. The cumulative effects of these situations will be analyzed by an inspection of internal battery parts when this test is completed.

Fig. 5. Nine month battery capacities at Sandia.

Controllers without low-voltage load disconnects have shown both recoverable and non-recoverable behavior when low-voltage battery conditions occurred. PV systems incorporating controllers without an LVD are vulnerable to excessive overdischarge of the battery if either the load exceeds the design or during extended periods of below average insolation. Two

Fig. 6. Nine month battery water additions at Sandia.

systems without an LVD experienced overdischarge of the batteries down to 1.5 volts per battery at both FSEC and Sandia. One controller allowed the PV array to remain connected to the battery without sufficient voltage being applied to operate the controller. After a few days, the PV array was able to recharge the battery without user intervention. The controller in the other system required battery voltage to operate, which without, did not allow the PV array to charge the battery. User intervention was required to return the system to normal operation.

Characterization Test Results

Data presented in this section are from characterization tests conducted at FSEC. Due to slight differences between controller set points at Sandia and FSEC, and the fact that a different numbering order was used, Table 2 describes the charge controllers at FSEC presented in Figs. 8-12. Also, to be consistent with the terminology in previous sections, graph legends are defined as follows: HVD refers to the battery regulation set point (VR), RCV refers to the battery regulation hysteresis (VRH), and LRV refers to the low voltage disconnect hysteresis (LVDH).

The data collected from the characterization tests can be graphically represented by a battery current versus battery voltage hysteresis plot. Figure 7 shows a typical family of these hysteresis curves for a shunt-type controller with LVD at 5, 25, and 45 °C, for a 5 amp PV and 5 amp load current. Referring to Fig. 7, one can follow the battery voltage as the controller disconnects and reconnects the PV array and load from the battery (1).

During characterizations, the simulated battery voltage is initially held at 10 volts while the controller is in a load disconnect condition with the PV array connected (5 amp battery current). As the battery voltage increases, the load is connected at the LVDH set point (battery current nearly zero). As the battery voltage is increased further, the controller eventually reaches the VR set point and disconnects the PV array. At this point, the load is supplied by the battery (-5 amp battery current). The battery voltage is then decreased until the VRH is reached, reconnecting the PV array to the battery. As the battery voltage is decreased further, the LVD set point is reached, returning the controller to the state at the beginning of the characterization test.

Table 2. Description of controllers at FSEC (25 °C).

System	VR	Temp Comp	Algorithm
1	14.31	No	Shunt-Interrupting
2	14.15	No	Series-Interrupting
3	14.60	Yes	Shunt-Interrupting
4	14.40	Yes	Shunt-Interrupting
5	14.22	No	Series-Interrupting PWM
6	14.66	Yes	Series Constant-Voltage
7	14.19	Yes	Shunt-Interrupting
8	—	Yes	Series-Multi-Step Constant-Current

Fig. 7. Hysteresis plot for shunt-type controller.

The controller setpoints and hysteresis or voltage span (VRH) for battery regulation are readily seen in Fig. 7. The battery regulation hysteresis is a critical factor in the performance of

charge controllers. A greater hysteresis generally results in lower PV array energy utilization, while a smaller hysteresis generally results in higher array energy utilization. Of course, the smaller the hysteresis, the higher the frequency of charge controller cycling. In addition to the battery regulation hysteresis, the load disconnect hysteresis (LVDH) and temperature effects on the charge controller set points are also shown in Fig. 7.

Fig. 8. Controller set points at 5 °C.

Figure 8 shows the measured set points for the three characterization tests at a temperature of 5 °C for the eight controllers at FSEC. The currents (both PV array and load) for the controllers were the maximum allowable for the specific unit. Note that Fig. 8 shows the stability, or consistency of the set points over several months of operation in the systems tests. Most controllers tested showed acceptable repeatability and stability of the set points. Also apparent in Fig. 8 are the relative values of the set points among the different controllers, and in particular, the hysteresis or span between the battery disconnect and reconnect set points for the PV array and load. Controllers #6 and #8 are shown to have a small battery regulation hysteresis (less than 0.1 volt), while controllers #2 and #4 have a large hysteresis (approximately 1.5 volt). In general, the battery SOC in systems #6 and #8 was considerably higher than in systems #2 and #4. The difference in the VR set point for controller #5 from the first to the second and third characterizations is due to an adjustment of the controller to obtain a higher set point after the first characterization.

Figure 9 shows the same information as Fig. 8, with the exception that the controller temperatures were 45 °C. Notice the decrease in the VR set point for controllers exhibiting

temperature compensation as compared with Fig. 8. The stability of the set points at 45 °C proved to be consistent with the results found at 5 °C. Most controllers showed no significant difference in the hysteresis of the controller set points from 5 to 45 °C.

Fig. 9. Controller set points at 45 °C.

Fig. 10. Controller set points at 5 and 45 °C.

To determine the temperature effects or temperature compensation on the controller set points, a comparison of the set points was made at 5 and 45 °C. The results of this comparison for the eight controllers used in the systems tests at FSEC are shown in Fig. 10 for the maximum allowable array and load currents. As shown, the set points for controllers #3, #4, #6 and #7 decrease appropriately as the temperature of the

Fig. 11. Controller temperature coefficients.

controller (or battery temperature probe) increases from 5 to 45 °C. On the other hand, controllers #1, #2, and #5 show very little, if any temperature compensation.

Fig. 12. LVD compensation coefficients.

Figure 11 shows the temperature coefficients in mV/°C/cell for both the battery regulation and load disconnect set points. All data presented are again for the maximum allowable load and PV array current through the controller. Controllers #4 and #6 show reasonable temperature coefficients of between -5 and -6 mV/°C/cell, controllers #3 and #7 demonstrates some compensation, while all other controllers do not appear to be affected by temperature. Tests conducted with the external temperature probe at ambient temperature, while the controller

was held at 5 and 45 °C, indicate that the temperature compensation of controller #4 is 50% due to the temperature of the probe, and 50% is due to the temperature of the controller. Controller #5 shows no temperature compensation due to the controller temperature compensation function being disabled. Also shown in Fig. 11 are the effects of temperature on the LVD set point. Data for controller #8 is not presented in Fig. 11.

Figure 12 illustrates the effect of PV and load current on LVD set points. Desirable trends would be that the LVD decreases with increased load. Controller #8 has a load current dependency on the LVD opposite of what is desirable, increasing from 11.0 to 11.5 volts as the load is increased from 0 to 10 amps. Although not shown here, a desirable characteristic of the VR set point would be a slight increase in the set point at higher battery charging currents. Controller #8 shows an increase in the battery regulation set point from 13.8 to 14.2 volts as the PV array current increases from 0 to 10 amps.

FIELD EVALUATIONS

Several sites with stand-alone PV lighting systems were visited to perform evaluations and gain a better understanding of charge controller operation in real systems. Each system was completely evaluated to expose conditions which may have been contributing to poor system performance. In general, most systems were functional, however, at a non-optimal performance. Typically, the batteries in the systems had operated for about a year and were found in generally poor condition due to lack of maintenance and improper charging. Both design and hardware related problems were found in most systems. A few of the more typical problems as related to charge controllers are listed below (7,8,9).

A common problem found in field evaluations was a mismatch of the charge controller VR set point and the battery. At one site where identical systems (and controllers) were installed, voltage regulation set points varied from 13.4 to 15.1 volts. Battery capacity tests proved the effects of the different set points. Where starved-electrolyte batteries were used, they have been typically overcharged due to a high VR set point. The sealed batteries have less tolerance to overcharging because once excessive gassing has occurred and electrolyte lost, it cannot be replenished, hence reduced battery lifetime. Flooded batteries, both lead-antimony and lead-calcium, were usually found to be undercharged and sulfated. This was caused by the VR set point adjusted too low. The tradeoff is low water requirements coupled with reduced battery capacity and lifetime.

Catalytic recombination caps have proven very effective in reducing battery water requirements to minimal levels. At one site where half of the systems have recombination caps and half do not, no water was required for the batteries with recombination caps over a six month period, while the batteries without these caps required over a gallon of water.

Load controls (timers and photocells) and LVDs have shown some problems during the field evaluations. Several system designs with oversized loads with respect to the PV array relied on the LVD to function as a load control. In these systems, the batteries remained at a low SOC almost continuously and indeed had a low load availability. The most trouble free lighting controls sense array voltage or current to turn the lights on and off at dusk and dawn. This eliminates the need to use photocells, which have been found to be unreliable in the field evaluations. All of the timers evaluated functioned as expected. A few controllers are available with light control/timers built-in, thus eliminating the need for additional components. A few systems were found with a non-functional LVD. One situation was encountered where the LVDH was too small, causing the load to cycle on and off rapidly at low battery SOC. A small LVDH may be desirable to increase load availability due to limited charging capabilities if battery lifetime is a secondary consideration.

Excessive voltage drops (in wiring, switches, fuses, etc.) have shown to be detrimental to the operation of many of the systems evaluated in the field. This has typically resulted in a loss of charging effectiveness of the PV array. Because the controller typically senses the battery voltage at the controller for the regulation set point, any voltage drops reduce the actual charging voltage at the battery. This was a factor in most systems with low battery capacity. Similarly, any excessive voltage drops in the load circuit reduce available voltage to the load, possibly reducing performance of the load. The use of improper wire sizes and connectors, lack of anti-oxidant grease on connections, and not using DC rated fuses and switches were the primary reasons for many voltage drop problems.

CONCLUSIONS

This evaluation program has shown a wide range of performance for the eight models of charge controllers evaluated. The controller set points and hysteresis windows are critical to the performance of the PV system. The algorithms, or how the charge controller provides the control of the set points, are also important features. Differences of as little as 200 mV in set point values can have significant effects on the resulting battery SOC and ultimately the life of the battery. System tests have

shown that hysteresis for control voltage is optimum between 300 mV and 1.1 V. Low voltage disconnect set points and hysteresis provide an option to the designer of either optimizing the availability of energy to the load or optimizing the battery SOC to reduce sulfation and increase life. Battery temperature compensation has been found to be essential when battery temperatures vary as little as $\pm 5^\circ\text{C}$. The field evaluations have revealed that charge controller performance, component mismatch, sizing errors, and installation deficiencies have contributed to premature battery failures in PV systems.

The data collected here are being used to provide feedback to designers and manufacturers of charge controller hardware and will be used to improve PV system sizing models and design handbooks. The information about charging algorithms, option performance, set points, hysteresis and battery technologies will allow designers to choose the most compatible components for a PV system.

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