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Comparison of Time Required to Charge a Battery in a Stand-Alone Photovoltaic System Using Different Charge Controller Types

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Abstract. An experiment was conducted at the National Renewable Energy Laboratory (NREL) comparing the time required to charge a fully discharged valve-regulated lead-acid battery in a photovoltaic (PV) system using on/off-shunt and pulse-width-modulated (PWM) charge controllers. In one system configuration, an on/off-shunt charge controller was only able to charge the battery to 61% of its rated capacity after 16 days. In a subsequent test, a different on/off-shunt controller in a different PV system configuration readily charged its battery to 100% rated capacity in less than 6 days. It charged its battery as quickly as a couple different PWM charge controllers did in identical systems in a side-by-side comparison.

INTRODUCTION

While first validating the "*Interim Test Methods and Procedures to Determine the Performance of Small PV Systems*,"[1] we noticed that a particular on/off-shunt charge controller seemed to be taking unusually long to charge a fully discharged PV system battery: despite having a period of good solar irradiance, the battery accepted 41% of its rated Ah capacity in the first four days of charging, but only an additional 20% in the following 12 days. The slow battery charging was attributed to the battery voltage reaching the array disconnect voltage (ADV) early each day, before the battery was completely charged. At this point, the charge controller would regulate or disconnect the array from the battery over a large percentage of the day while maximum solar energy was available. Using a stopwatch on several occasions during the last 12 days of charging, we estimated the percentage of solar energy shunted away from the batteries to be approximately 90%. The usable capacity withdrawn from the battery was measured to be only 56%, with a battery temperature range of 2° to 12°C. The battery manufacturer specifies the capacity in this temperature range to be approximately 90%. Based on this information, we suspected that on/off controllers might charge batteries slower than other types of controllers. We conducted an experiment with three identical PV systems set up side by side with a different charge controller in each: an on/off-shunt, a constant-voltage pulse-width-modulated (PWM), and a three-stage PWM.

This paper presents the experiment and the results of the test. This paper does not address the issue of how charge-controller technology affects battery lifetime.

TEST PROCEDURE

We used the system autonomy procedure in the "*Interim Test Methods and Procedures for Determining the Performance of Small PV Systems*"[1], which is used to indicate how long the energy in a fully charged battery can operate the load with no contribution from the PV array. This test, performed after the battery has been cycled (charged and discharged) several times, can only be run on systems with a battery protected by low-voltage disconnect (LVD) circuitry.

First, the PV array is disconnected and the load is operated until the battery is fully discharged. This provides a starting reference point, having withdrawn all usable capacity from the battery. In this test, the battery is defined to be fully discharged when it reaches LVD. Next, the load is disconnected and the array reconnected. While monitoring the battery voltage, current, amp-hours (Ah), battery temperature, and solar irradiance, the battery is charged by the PV array. In this test, the battery is considered fully charged after the charge controller begins regulating and after the battery has accepted 125% of its rated Ah capacity. We chose the 125% value to account for the inefficiency of lead-acid batteries [2]; this value may change as we gain experience with different batteries. Finally, the array is disconnected and the load reconnected. While monitoring the battery voltage, current, Ah, and battery temperature, the load operates until the battery is low-voltage disconnected by the charge controller. The system autonomy is calculated by dividing the number of Ah withdrawn from the battery by the number of Ah consumed by the load during normal daily system operation. System autonomy is commonly referred to as "days of autonomy."

DESCRIPTION OF SYSTEMS

Table 1 contains the specifications for the four systems that were included in this comparison. System #0 is the system that prompted us to investigate battery charge-time using the other three systems. System #0 is a 24-V system, whereas the other three are 12-V. The charge-controller setpoints in System #0 (in parentheses) are provided as a comparison against the setpoints of the other three 12-V controllers. Systems #1, #2, and #3 are identical, with the exception of their charge controllers. The controllers in Systems #0 and #1 are on/off-shunt types from two different manufacturers and have different setpoints. System #2 has a constant-voltage PWM controller, and System #3 has a 3-stage PWM controller. The controller setpoints of Systems #0 and #2 were not adjustable, and no information was provided to adjust the controller in System #1. The voltage setpoints for Systems #0 and #2 were taken from the manufacturers' literature; those of System #2 were measured during a bench test; and those of System #3 were set at NREL. LVD circuitry is built into all four charge controllers.

The array in System #1 is single-crystalline silicon (c-Si), and Systems #1, #2, and #3 have triple-junction amorphous silicon (a-Si/a-Si/a-Si) modules. All four systems use sealed gelled valve-regulated lead-acid (VRLA) batteries. The load in System #0 is an 18-W low-pressure sodium (LPS) lamp that normally operates 24 hours a day. The other loads are a pair of 8-W fluorescent lamps that normally operate 4 hours per night.

TABLE 1. System Specifications

		System #0	System #1	System #2	System #3
Array	Material	c-Si[1]	a-Si/a-Si/a-Si[2]	a-Si/a-Si/a-Si	a-Si/a-Si/a-Si
	P_{max} (W)	212	32	32	32
	V_{max} (V)	34.8	16.5	16.5	16.5
	I_{max} (A)	6.1	1.9	1.9	1.9
	V_{oc} (V)	43.4	23.8	23.8	23.8
	I_{sc} (A)	6.8	2.4	2.4	2.4
	Tilt (degrees)	50	50	50	50
Load	Type	18-W LPS[3] Lamp	16-W F[4] Lamp	16-W F Lamp	16-W F Lamp
	Nominal Voltage	24.0	12.0	12.0	12.0
	Current	0.75	1.33	1.33	1.33
	Ah/Day	18.0	5.3	5.3	5.3
Solar Radiation[5] [3]	kWh/m2/day	4.5	4.5	4.5	4.5
Array-to-Load Ratio		1.5	1.6	1.6	1.6
Battery	Type	VRLA Gelled	VRLA Gelled	VRLA Gelled	VRLA Gelled
	Nominal Voltage	24	12	12	12
	Capacity (Ah)	198	60	60	60
Days of Autonomy[6]		7	7	7	7
Controller	Type	On/Off-Shunt	On/Off-Shunt	Constant-Voltage PWM	3-Stage PWM
	ADV[7] (V)	28.6 (14.3)	14.9	14.1	14.1
	ARV[8] (V)	27.0 (13.5)	13.2	n/a	13.5
	LRV[9] (V)	26.0 (13.0)	12.3	12.7	13.0
	LVD[10] (V)	23.0 (11.5)	11.3	11.5	11.5
	Setpoints Adjustable?	no	yes	no	yes
	Temp Compensation?	external	none	internal	external
Notes:					
1 - Single-crystalline silicon					
2 - Triple-junction amorphous silicon					
3 - Low-pressure sodium lamp					
4 - Fluorescent lamp					
5 - Minimum monthly daily average solar radiation for a flat-plate array at a 55-degree tilt for 1 year					
6 - Assuming 80% battery efficiency and 80% depth of discharge					
7 - Array Disconnect Voltage					
8 - Array Reconnect Voltage					
9 - Load Reconnect Voltage					
10 - Load Disconnect Voltage					

System #0 operated from October 1997 until February 1998 before the system autonomy test was conducted from 23 February through 18 March 1998. The other systems operated from April 1998 until July 1998 before testing began.

TEST RESULTS

The fact that it took so long for the on/off-shunt controller in System #0 to charge its battery, and that its usable capacity was significantly lower than its rated value, was the motivation that led to the testing with the other systems. Three small PV systems, identical in every way except for their charge controllers, were run side by side. During battery charging, all three batteries accepted 100%-rated Ah capacity within 6 days (Figs. 1, 2, and 3). This is in line with the calculated number of days required to charge the battery to the 100% level at that time of the year at this location:

$$60 \text{ Ah} / (1.9 \text{ A} \times 5.3 \text{ h/day}) = 5.96 \text{ days}, \quad (1)$$

where 60 Ah is the nominal capacity of the battery, 1.9 A is the array current at P_{max}, and 5.3 h/day is the minimum monthly daily average solar radiation for a flat-plate array at a 55° tilt [3]. (In fact, we calculated that System #0 should have fully charged its battery in about 6 days, too.) The 125% level was exceeded after 8 days by the on/off-shunt controller in System #1 (Fig. 1), after 9 days by the constant-voltage PWM controller in System #2 (Fig. 2), and after 11 days with the 3-stage PWM controller in System #3 (Fig. 3).

Using the load to discharge the battery while the array was disconnected, the system capacities were all found to be above their rated capacity. Battery temperatures ranged from 18° to 31°C during the discharge test. Battery capacity in this temperature range is specified to be slightly above 100% of rated capacity.

Comparison of Results

From the results encountered with System #0, we expected that all on/off charge controllers might significantly slow the charging of a PV system battery, but the results from System #1 contradict this. The on/off-shunt controller charged its battery to its rated capacity just as quickly as the batteries charged with two different kinds of PWM charge controllers.

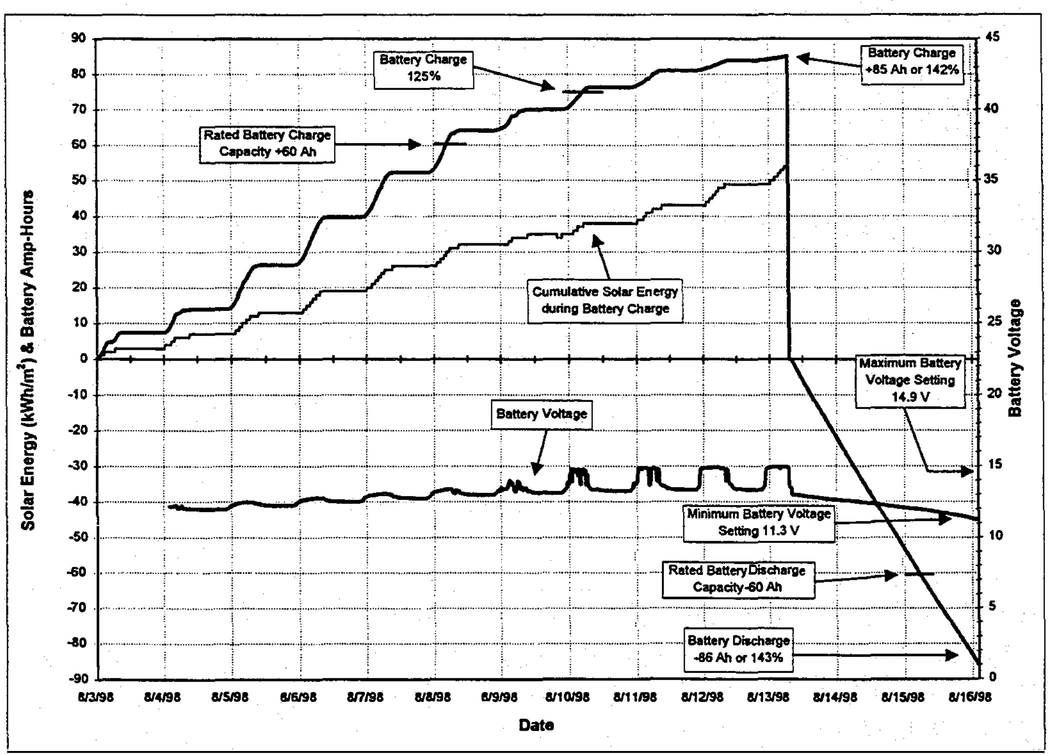

FIGURE 1. PV System #1 battery charging and discharging with an on/off-shunt charge controller (14.9/13.2/12.3/11.3 V), 32-W a-Si array, and 12 V / 60 Ah VRLA battery.

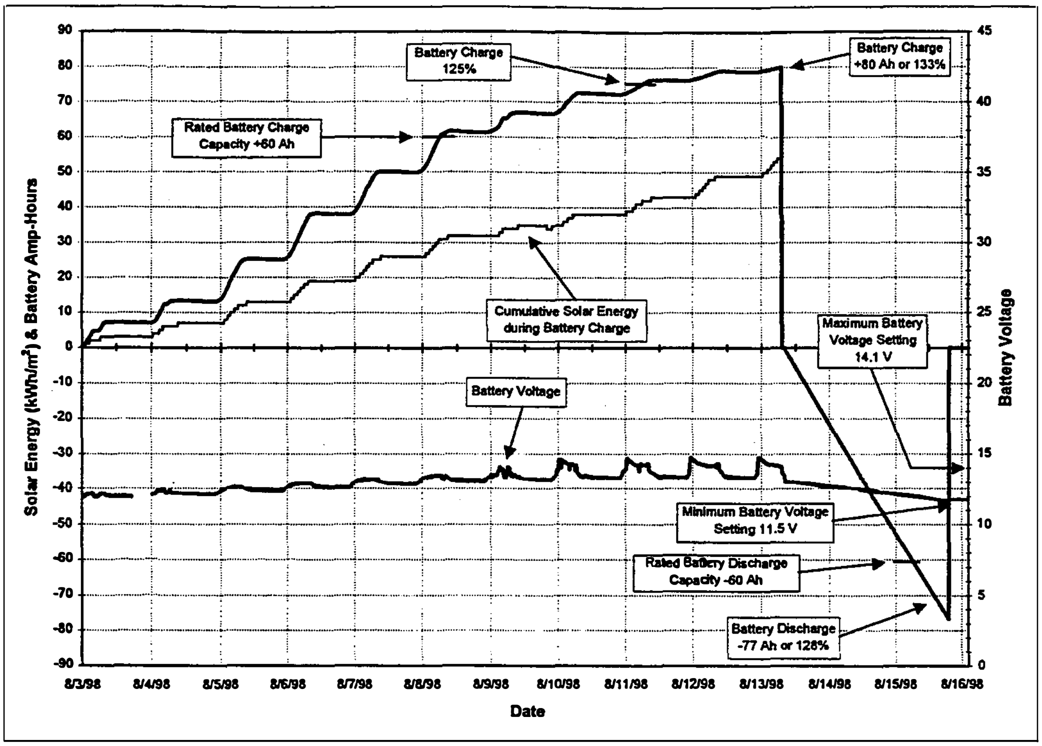

FIGURE 2. PV System #2 battery charging and discharging with a constant-voltage PWM charge controller (14.1/12.7/11.4V), 32-W a-Si array, and a 12 V/60 Ah VRLA battery.

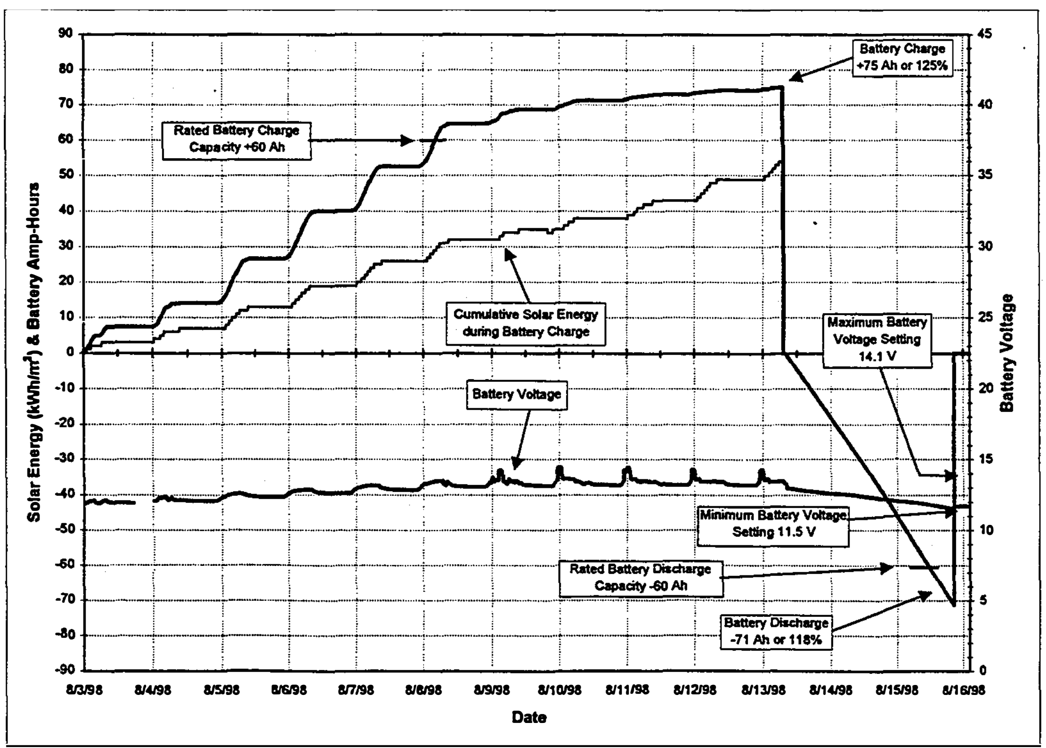

FIGURE 3. PV System #3 battery charging and discharging with a 3-stage PWM charge controller (14.1/13.5/13.0/11.5V), 32-W a-Si array, and a 12 V/60 Ah VRLA battery.

SUMMARY

Although the preliminary results from one system suggest that on/off controllers in general might not charge PV system batteries as quickly as other types of controllers, the results of our side-by-side PV charge-controller experiment show that in this particular set up, and under these particular conditions, an on/off-shunt controller can charge a PV system battery as quickly as PWM controllers. Further research will be conducted at NREL to try to determine what factors caused the battery in System #0 to charge so slowly. Some factors might include controller setpoints; array size and material; battery age, temperature, size, and type; depth of battery discharge; load size and type; and the weather at the site. We will try to quantify the effect each of these factors has on the ability of different types of charge controllers to charge batteries in stand-alone PV systems.

This experiment points out how important it is to examine the operation of a complete PV system. The system interfaces and site conditions have to be looked at as a whole to determine the performance of the system.

Knowing the time required to charge a lead-acid battery in a PV system, and how much energy can be extracted from it, is important in designing optimized PV systems that will operate reliably to meet the needs of users.

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