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Why PWM?

The technology for solar photovoltaic battery charge controllers has advanced dramatically over the past five years. The most exciting new technology, PWM charging, has become very popular. Some *Frequently Asked Questions* about PWM battery charging are addressed here.

What is PWM?

Pulse Width Modulation (PWM) is the most effective means to achieve constant voltage battery charging by switching the solar system controller's power devices. When in PWM regulation, the current from the solar array tapers according to the battery's condition and recharging needs.

Why is there so much excitement about PWM?

Charging a battery with a solar system is a unique and difficult challenge. In the "old days," simple on-off regulators were used to limit battery outgassing when a solar panel produced excess energy. However, as solar systems matured it became clear how much these simple devices interfered with the charging process.

The history for on-off regulators has been early battery failures, increasing load disconnects, and growing user dissatisfaction. PWM has recently surfaced as the first significant advance in solar battery charging.

PWM solar chargers use technology similar to other modern high quality battery chargers. When a battery voltage reaches the regulation setpoint, the PWM algorithm slowly reduces the charging current to avoid heating and gassing of the battery, yet the charging continues to return the maximum amount of energy to the battery in the shortest time. The result is a higher charging efficiency, rapid recharging, and a healthy battery at full capacity.

In addition, this new method of solar battery charging promises some very interesting and unique benefits from the PWM pulsing. These include:

1. Ability to recover lost battery capacity and desulfate a battery.
2. Dramatically increase the charge acceptance of the battery.

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3. Maintain high average battery capacities (90% to 95%) compared to on-off regulated state-of-charge levels that are typically 55% to 60%.
4. Equalize drifting battery cells.
5. Reduce battery heating and gassing.
6. Automatically adjust for battery aging.
7. Self-regulate for voltage drops and temperature effects in solar systems.

These benefits are discussed in more detail in the following addendum.

How does this technology help me?

The benefits noted above are technology driven. The more important question is how the PWM technology benefits the solar system user.

Jumping from a 1970's technology into the new millennium offers:

- **Longer battery life:**
  - reducing the costs of the solar system
  - reducing battery disposal problems
- **More battery reserve capacity:**
  - increasing the reliability of the solar system
  - reducing load disconnects
  - opportunity to reduce battery size to lower the system cost
- **Greater use of the solar array energy:**
  - get 20% to 30% more energy from your solar panels for charging
  - stop wasting the solar energy when the battery is only 50% charged
  - opportunity to reduce the size of the solar array to save costs
- **Greater user satisfaction:**
  - get more power when you need it for less money!!

Are all of these benefits tested and proven?

A great deal of testing and data supports the benefits of PWM. More information is attached that describes the technology and various studies.

Morningstar will continue our ongoing test programs to refine the PWM charging technology. Over time, each of these benefits will be improved and more clearly defined with numbers and graphs.

Are all PWM chargers the same?

Buyer beware! Many solar charge controllers that simply switch FETs differently than the on-off algorithm claim to be a PWM charger. Only a few controllers are actually using a Pulse Width Modulated (PWM) constant voltage charging algorithm. The rest are switching FETs with various algorithms that are cheaper and less effective.

Morningstar was awarded a patent in 1997 for a highly effective battery charging algorithm based on true PWM switching and constant voltage charging. All Morningstar products use this patented algorithm.

1. Ability to recover lost battery capacity

According to the Battery Council International, 84% of all lead acid-battery failures are due to sulfation. Sulfation is even more of a problem in solar systems, since "opportunity charging" differs significantly from traditional battery charging. The extended periods of undercharging common to solar systems causes grid corrosion, and the battery's positive plates become coated with sulfate crystals.

Morningstar's PWM pulse charging can deter the formation of sulfate deposits, help overcome the resistive barrier on the surface of the grids, and punch through the corrosion at the interface. In addition to improving charge acceptance and efficiency, there is strong evidence that this particular charging can recover capacity that has been "lost" in a solar battery over time. Some research results are summarized here.

A 1994 paper by CSIRO, a leading battery research group in Australia (reference 1), notes that pulsed-current charging (similar to Morningstar controllers) "has the ability to recover the capacity of cycled cells." The sulfate crystallization process is slowed, and the inner corrosion layer becomes thinner and is divided into islands. The electrical resistance is reduced and capacity is improved. The paper's conclusion is that pulse charging a cycled battery "can evoke a recovery in battery capacity."

Another paper, a Sandia National Labs study in 1996 (reference 2, attached), summarizes testing of a VRLA battery that had "permanently" lost over 20% of its capacity. Conventional constant voltage charging could not recover the lost capacity. Then the battery was charged with a Morningstar SunSaver controller, and "much of the battery capacity has been recovered."

Finally, Morningstar has been testing for capacity recovery. An attached graph (reference 3, attached) shows how a battery that was "dead" recovered much of its lost capacity after extended charging with a SunLight controller.

After the test was set-up, for 30 days the solar lighting system produced virtually no lighting since the system went directly into LVD each night. The battery was very old and about to be recycled. Then, the load began to turn on longer each night as shown on the graph. For the next 3 months the battery capacity steadily increased. This test and other capacity recovery tests are ongoing at Morningstar.

2. Increase battery charge acceptance

Charge acceptance is a term often used to describe the efficiency of recharging the battery. Since solar batteries are constantly recharging with a limited energy source (e.g. opportunity charging with available sunlight), a high charge acceptance is critical for required battery reserve capacity and system performance.

Solar PV systems have a history of problems due to poor battery charge acceptance. For example, a study of four National Forest Service lighting systems (reference 4) using on-off shunt controllers clearly demonstrated the problems caused by low charge acceptance. The batteries remained at low charge states and went into LVD every night, but the battery typically accepted only about one-half the available solar energy the next day during charging. One system only accepted 10% of the energy available from the array between 11:00 AM and 3:00 PM!

After extensive study, it was determined that "the problem is in control strategy, not in the battery." Further, "the battery was capable of accepting that charge, but it wasn't being charged." Later a system "similar in all respects" except using a constant voltage charge controller was studied. In this case, the "battery is being maintained in an excellent state of charge."

A later study specific to Morningstar's PWM constant voltage charging by Sandia (reference 2, attached) found that the SunSaver's "increased charge acceptance is due to the PWM charge algorithm." Tests showed that the SunSaver

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provided 2 to 8% more overcharge compared to a conventional DC constant voltage charger.

A number of tests and studies have demonstrated that Morningstar's PWM algorithm provides superior battery charge acceptance. An attached graph (reference 5, attached) compares the recharging ability of a Morningstar SunSaver PWM controller with a leading on-off regulator. This study, done by Morningstar, is a side-by-side test with identical test conditions. The PWM controller put 20% to 30% more of the energy generated by the solar array into the battery than the on-off regulator.

3. Maintain high average battery capacities

A high battery state-of-charge (SOC) is important for battery health and for maintaining the reserve storage capacity so critical for solar system reliability. An FSEC Test Report (reference 6) noted that "the life of a lead-acid battery is proportional to the average state-of-charge," and that a battery maintained above 90% SOC "can provide two or three times more charge/discharge cycles than a battery allowed to reach 50% SOC before recharging."

However, as noted in the previous section, many solar controllers interfere with the recharging of the battery. The FSEC study noted at the end of the report that the "most significant conclusion is that some controllers did not maintain the battery SOC at a high level, even when loads were disconnected."

In addition, a comprehensive 23 month study of SOC factors was reported by Sandia in 1994 (reference 7, page 940, attached). It was learned that the regulation setpoint has little effect on long-term SOC levels, but the reconnect voltage is strongly correlated to SOC. Five on-off regulators and two quasi constant voltage regulators were tested (Morningstar controllers were not developed when this test started). A summary of the SOC results follows:

- 3 on-off regulators with typical hysteresis averaged between 55% and 60% SOC over the 23 month period
- 2 on-off regulators with tighter hysteresis (risking global instability) averaged about 70% SOC
- the 2 "constant voltage" controllers with hysteresis of 0.3 and 0.1 volts averaged close to 90% SOC (note that Morningstar controllers have a "hysteresis" of about 0.020 volts)

Sandia concluded that the number of times a system cycles off and on during a day in regulation has a much stronger impact on battery state-of-charge than other factors within any one cycle. Morningstar's PWM will "cycle" in regulation 300 times per second.

It would be expected that batteries charged with Morningstar's PWM algorithm will maintain a very high average battery state-of-charge in a typical solar system. In addition to providing a greater reserve capacity for the system, the life of the battery will be significantly increased according to many reports and studies.

4. Equalize drifting battery cells

Individual battery cells may increasingly vary in charge resistance over time. An uneven acceptance of charge can lead to significant capacity deterioration in weaker cells. Equalization is a process to overcome such unbalanced cells.

The increased charge acceptance and capacity recovery capabilities of PWM pulse charging will also occur at lower charging voltages. Morningstar's PWM pulse charging will hold the individual battery cells in better balance where equalization charges are not practical in a solar system.

More testing will be done to study the potential benefits is this area.

5. Reduce battery heating and gassing

Clearly battery heating/gassing and charge efficiency go hand in hand. A reduction in transient gassing is a characteristic of pulse charging. PWM will complete the recharging job more quickly and more efficiently, thereby minimizing heating and gassing.

The ionic transport in the battery electrolyte is more efficient with PWM. After a charge pulse, some areas at the plates become nearly depleted of ions, whereas other areas are at a surplus. During the off-time between charge pulses, the ionic diffusion continues to equalize the concentration for the next charge pulse.

In addition, because the pulse is so short, there is less time for a gas bubble to build up. The gassing is even less likely to occur with the down pulse, since this pulse apparently helps to break up the precursor to a gas bubble which is likely a cluster of ions.

6. Automatically adjust for battery aging

As batteries cycle and get older, they become more resistant to recharging. This is primarily due to the sulfate crystals that make the plates less conductive and slow the electro-chemical conversion.

However, age does not affect PWM constant voltage charging.

The PWM constant voltage charging will always adjust in regulation to the battery's needs. The battery will optimize the current tapering according to its internal resistance, recharging needs, and age. The only net effect of age with PWM charging is that gassing may begin earlier.

7. Self-regulate for voltage drops and temperature effects

With PWM constant voltage charging, the critical finishing charge will taper per the equation $I = Ae^{-t}$. This provides a self-regulating final charge that follows the general shape of this equation.

As such, external system factors such as voltage drops in the system wires will not distort the critical final charging stage. The voltage drop with tapered charging current will be small fractions of a volt. In contrast, an on-off regulator will turn on full current with the full voltage drop throughout the recharging cycle (one reason for the very poor charge efficiency common to on-off regulators).

Because Morningstar controllers are all series designs, the FET switches are mostly off during the final charging stages. This minimizes heating effects from the controller, such as when they are placed inside enclosures. In contrast, the shunt designs will reach maximum heating in the final charging stage since the shunt FETs are switching almost fully on.

In summary, the PWM constant voltage series charge controller will provide the recharging current according to what the battery needs and takes from the controller. This is in contrast to simple on-off regulators that impose an external control of the recharging process which is generally not responsive to the battery's particular needs.

References:

1. Lam, L.T., et al, 'Pulsed-current charging of lead/acid batteries—a possible means for overcoming premature capacity loss?,' CSIRO, Australia, *Journal of Power Sources* 53, 1995.
2. Hund, Tom, 'Battery Testing for Photovoltaic Applications,' Sandia National Laboratories, Albuquerque, NM, presented at *14th NREL Program Review*, Nov. 1996.
3. Morningstar test results, 1999.
4. Stevens, John et al, 'Field Investigation of the Relationship Between Battery Size and PV System Performance,' Sandia National Laboratories, Albuquerque, NM.
5. Morningstar test results, 1999.
6. Dunlop, James et al, 'Performance of Battery Charge Controllers: An Interim Test Report,' Florida Solar Energy Center, Cape Canaveral, FL, presented at *IEEE PV Specialists Conference*, May 1990.
7. Woodworth, Joseph et al, 'Evaluation of the Batteries and Charge Controllers in Small Stand-Alone Photovoltaic Systems.' Sandia National Laboratories, presented at *WCPEC*, December 1994.

Preprint from the 14th NREL Photovoltaic Program Review, November 1996

PV CHARGE CONTROLLER AND FIELD TESTING

Sandia is now working with Morningstar and Digital Solar Technologies to test lower cost, improved performance, and higher reliability charge controllers such as the SunSaver PWM charge controller and the MPR-9400 microprocessor based PV charge controller. Some examples of this work are identified below.

Morningstar SunSaver™

The development of this charge controller was partially funded by Sandia as part of DOE's Photovoltaic BOS Program. The SunSaver™ has been in field tests for over six months. The SunSaver™ has demonstrated exceptional performance and reliability for a small (<10 amps) low cost PV charge controller. It increases charge acceptance in VRLA batteries which should improve VRLA battery cycle-life. The increased charge acceptance is due to the PWM charge algorithm. Previous work[11] has indicated that improved charge acceptance is possible "...by discharging prior to charging or during the charging process". Figure 8 is an example of the PWM charging algorithm in the SunSaver™. The charge and discharge current pulses may be responsible for the improved charge acceptance seen when used with VRLA batteries. Field tests have shown that the SunSaver™ does provide VRLA batteries with a much higher overcharge or charge acceptance.

Figure 9 is an example of how the PV Battery Cycle-Life Test can be used to evaluate battery charge acceptance. In this test the Morningstar SunSaver™ was placed in series with the Firing Circuits automated battery tester to make a direct comparison between DC constant voltage charging and PWM charging using the same VRLA battery and test program for both charge algorithms. This battery survived over 200 cycles of the PV Battery Cycle-Life Test before it "permanently" lost over 20% of its capacity (99 to 73 Ah). The battery capacity could not be recovered with constant voltage charging using recommended charging procedures. SunSaver™ PV Battery Cycle-Life Test results now indicate that much of the battery capacity has been recovered. This is illustrated by the deficit charge cycle which removed 74 Ah at 11.46 volts. Previous capacity tests on this battery resulted in about 10 Ah of battery capacity between 11.5 and 10.5 volts. This indicates that an increase in battery capacity of about 11 Ah has occurred from the SunSaver™ PWM PV charge controller.

Preprint from the 14th NREL Photovoltaic Program Review, November 1996

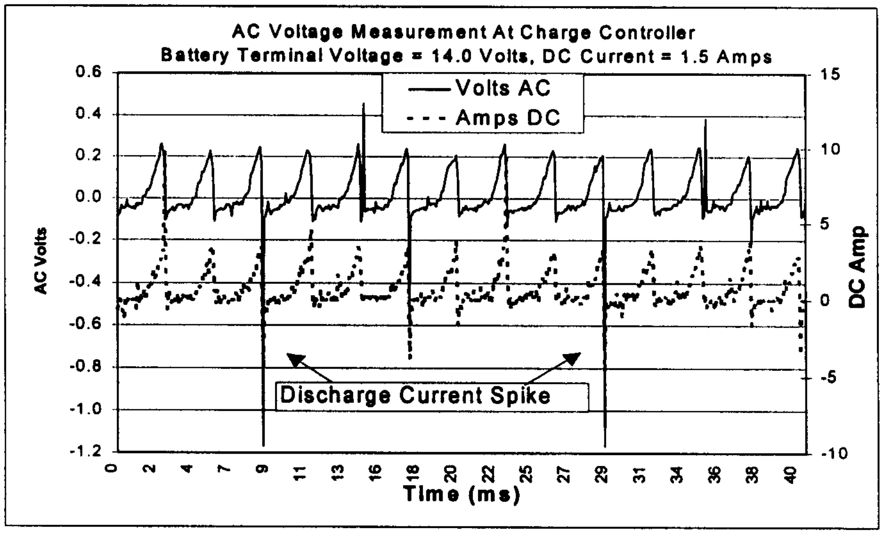

Figure 8. SunSaver™ Pulse Width Modulated Charging Showing Charge and Discharge Current Spikes

The test results in Figure 9 also indicate that the Morningstar SunSaver™ is providing the GNB 12-5000X AGM VRLA battery with 2 to 8% more overcharge compared to the constant voltage charge algorithm. In addition to the increased overcharge, the PWM charge controller is charging at 14.0 volts instead of 14.1 volts due to a voltage drop from the internal electrical resistance in the battery tester. The SunSaver™ is also charging the battery at about 25°C compared to the constant voltage data at about 27°C.

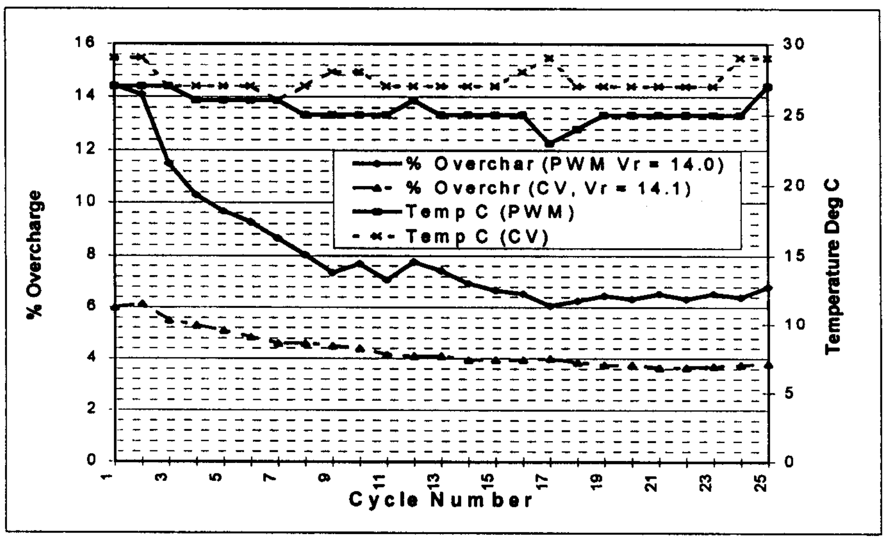

Figure 9. PV Battery Cycle-Life Test Comparing Constant Voltage Charging vs. The SunSaver™ Pulse Width Modulated Charging Using A GNB 12-5000X VRLA Battery

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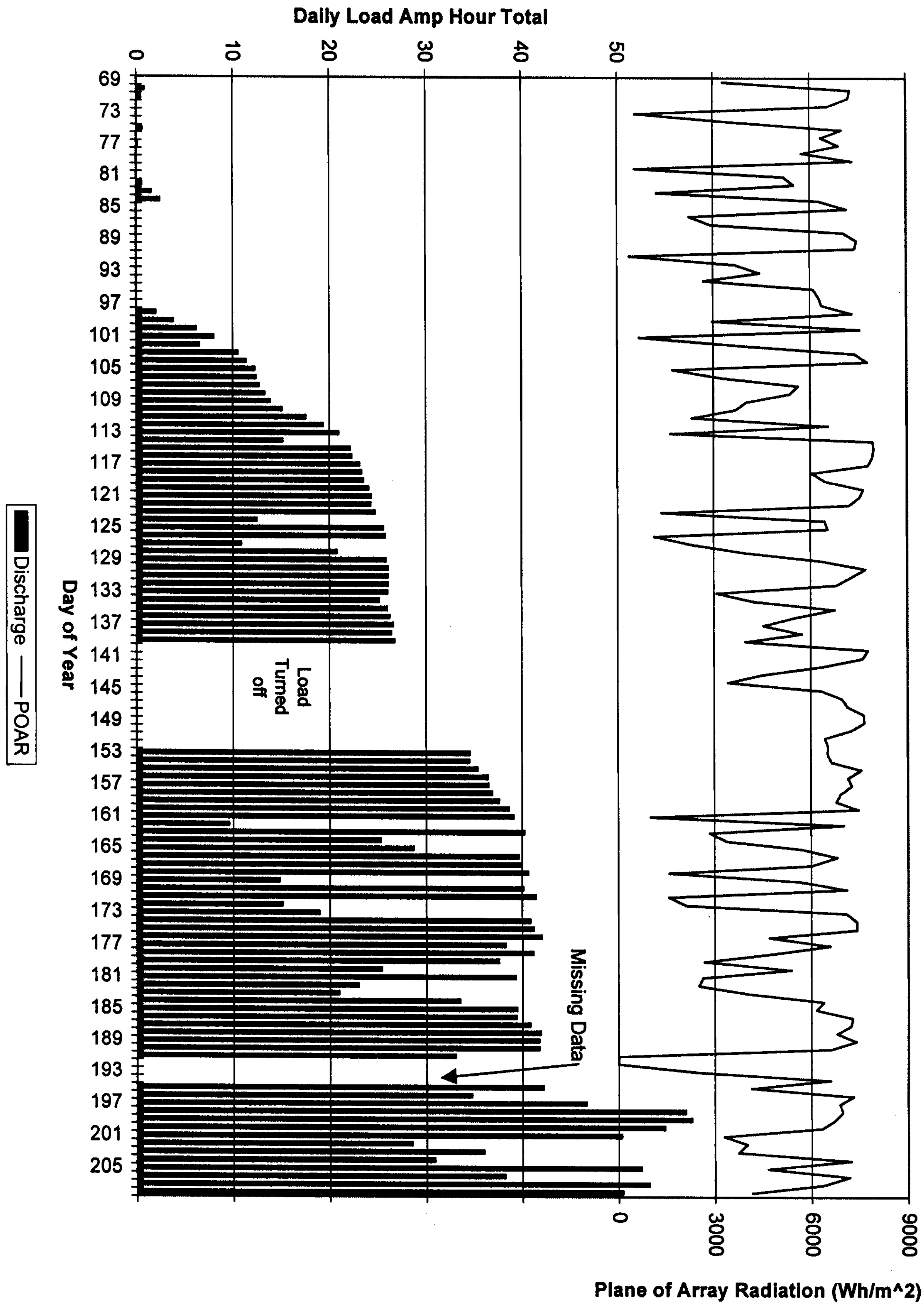
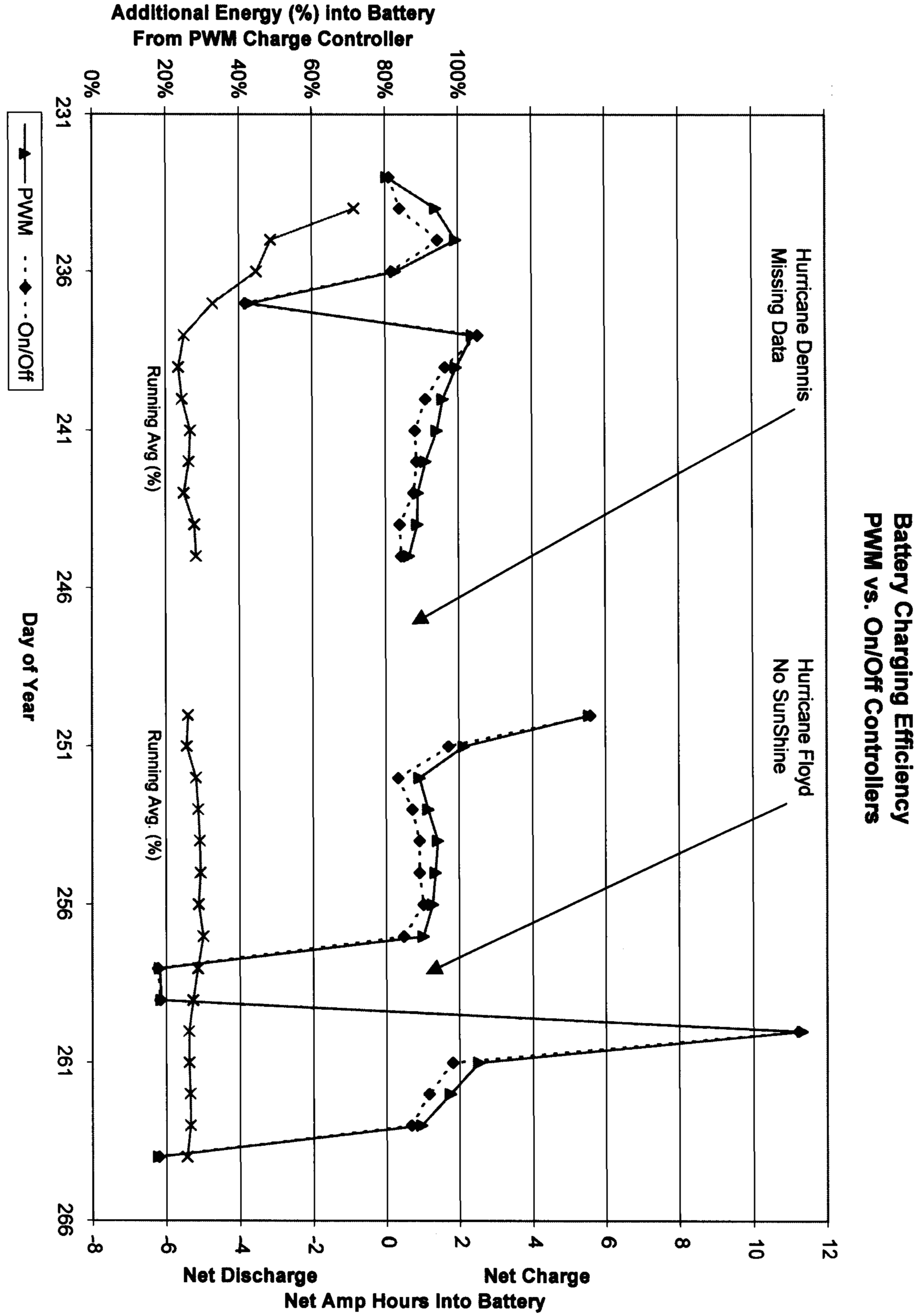

Daily Load Amp Hour Total
Day of Year
Plane of Array Radiation (Wh/m^2)
Load Turned off
Missing Data
Discharge
POAR


Battery Charging Efficiency
PWM vs. On/Off Controllers
Additional Energy (%) into Battery
From PWM Charge Controller
Hurricane Dennis
Missing Data
Hurricane Floyd
No SunShine
Running Avg (%)
Running Avg. (%)
PWM
On/Off
Day of Year
Net Discharge
Net Charge
Net Amp Hours Into Battery

in which the batteries were bulk charged to 14.4 V and then held at 14.4 V for 30 hours (this third set of data is not shown in Fig. 7) . Surprisingly, the solar irradiances at four months (February) and eight months (June) were about the same at FSEC, allowing a meaningful comparison between the two different periods. We conclude that systems 2 through 5 have increased their average state-of-charge by only about 6% during the three days without a load on the system.

ANALYSIS

Are charge controllers really necessary?

The systems described in this paper have battery capacities equal to ~ 4 days of load requirements and are typical of many PV systems used for residential or outdoor lighting applications. The function of the charge controllers in these systems is to protect the batteries from overcharge or overdischarge. There are PV designs which operate satisfactorily without charge controllers. As an example, when load requirements are much smaller than in the systems described here, it is often economical to omit the charge controller entirely and use a battery with a capacity of ~30 days of load requirements instead. The U. S. Coast Guard has used this type of design in many navigational beacons. While the batteries in these navigational systems do suffer from the effects of overcharging and overdischarging, the relatively large battery capacity allows these systems to continue to operate reliably.[20]

Two systems in this test with malfunctioning or incomplete charge controllers demonstrate why controllers are needed for the types of PV systems tested here. System #1 at FSEC initially had a malfunctioning controller that rarely regulated at all and which, on most clear days, continued to try to bulk charge the battery until sunset. This led to maximum battery voltages of 15.0 to 15.3 V on many sunny days, which is excessive for this type of battery. As a result, the battery in system # 1 had very high water loss (see Figure 16) and in the post-mortem inspection, the positive grids of this battery were found to be severely corroded. On the other hand, system # 3 at Sandia initially had no low-voltage disconnect. As a result, the battery in this system was drained to ~1.5 V during a cloudy period in January 1991. At 1.5 V, the controller could not operate properly and disconnected the array from the battery, locking the system into a non-functioning state. Manual intervention was required to restart the system. An external low-voltage disconnect was added to the system after this incident. Note that this problem, which occurred due to the absence of a low voltage disconnect, occurred on the system which otherwise maintained the highest state-of-charge of any of the fourteen systems in this test.

Set Points

The differing set points of the systems at Sandia allow us to look at the effect of the set points on the system's state-of-charge. Figure 9 plots the average system state-of-charge over the 23 months of the test as a function of Vr. Vr values

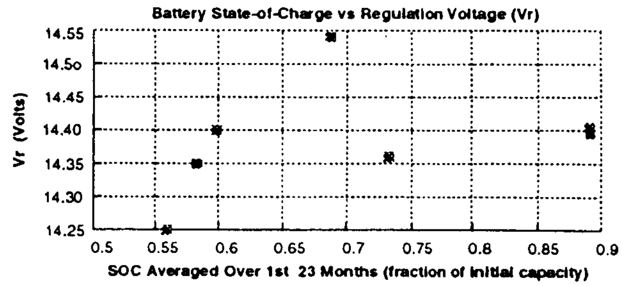


Figure 9: Average state-of-charge of the batteries at Sandia over the 23-month test as a function of regulation voltage (Vr) of the charge controller. Note the absence of any obvious correlation.

at Sandia had been set as close as possible to 14.4 V, therefore we could only examine the effect of Vr over a limited range. Over this limited range, there does not appear to be any correlation between Vr and state-of-charge. Figure 10 shows a plot of the average system state-of-charge as a function of the value of Vrr, the regulation reconnect voltage. This data shows a strong correlation, with a correlation coefficient (R)[21] of 0.95. Analysis of the correlation coefficient and the number of data points indicates that the probability (P)[21] that this apparent correlation is accidental is less than 0.1%. Figure 11 shows a plot of total water loss at Sandia over the 23 months of the experiment as a function of Vrr. Again, we see a significant correlation with R = 0.88 and P = 1%. Plots of water loss versus Vr show no obvious correlation for the Sandia data. Finally, Figure 12 shows that system state-of-charge and water loss are also correlated with each other (R = 0.89, P = less than 1%).

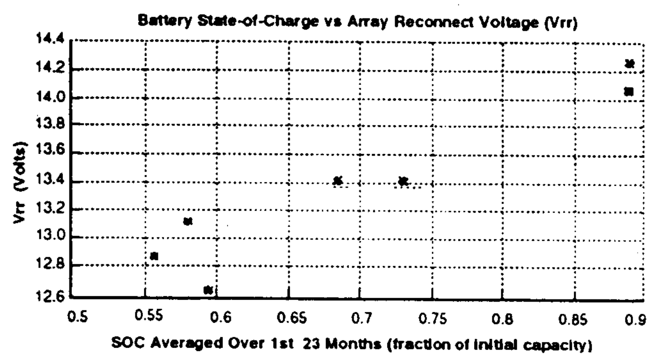


Figure 10: Average state-of-charge of the batteries at Sandia over the 23-month test as a function of regulation reconnect voltage (Vrr). Note that state-of-charge is strongly correlated to Vrr.

Both state-of-charge and water loss are strongly dependent on regulation reconnect voltage, but only weakly dependent on regulation voltage over the range of the Vr and Vrr data shown. It appears that the number of times a system cycles off and on during a day in regulation has a much stronger impact on battery state-of-charge than the maximum voltage

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