CHARGE CONTROLLER PROFILES

Charge controllers can have different algorithms for regulating the current and voltage from a PV array, which are illustrated in daily profile plots. Sample charge controller profiles have been compiled from tests on PV lighting systems at the Florida Solar Energy Center (FSEC). The outdoor lights are designed to turn ON at dusk and OFF at dawn, operating overnight from batteries that are charged from PV arrays during the day. Each test was conducted under the same conditions using identical batteries, arrays, loads, and other system equipment that are typical of commercially available PV lighting systems. The only difference was the charge controller.

The measured parameters include solar irradiance, battery voltage (V_{bat}), battery current (I_{bat}), array voltage (V_{array}), and array current (I_{array}). Each parameter was sampled every 10 seconds and averaged over a six minute period. The minimum and maximum of the battery voltage samples were recorded every six minutes.

Note: Since these test systems were originally designed to investigate not only the behavior of the different controllers but also how regulation setpoints affect battery state-of-charge, the setpoints were not always optimized for the specific system design. However, these daily profiles still effectively show the charge controller operation.

Shunt-Interrupting Charge Controllers

A shunt-interrupting charge controller suspends charging current to a battery system by short-circuiting the array through a shunt element inside the charge controller. This moves the array's operating point on the I-V curve to very near the short-circuit condition, limiting the power output. When the battery voltage falls, the controller reconnects the array to resume charging. This ON/OFF cycling may occur over a period of several minutes or a few seconds, depending on the charge rate and battery state-of-charge.

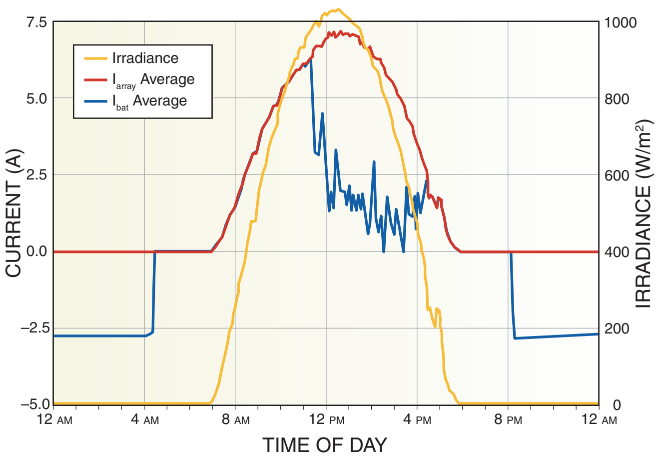
During the night, the load is operating and battery voltage decreases steadily to about 11.9 V while being discharged. At about 4:30 AM, the load is disconnected by the charge controller timing circuit. At this point, the battery current falls to 0 A, and there is a sharp rise in the battery voltage to an open-circuit (no load) voltage of about 12.35 V.

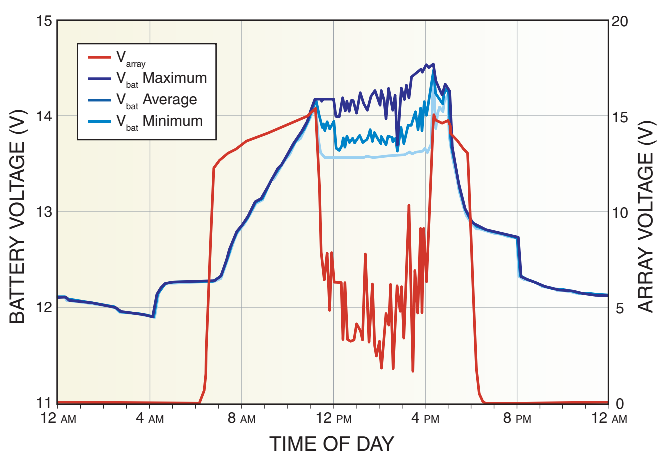
At sunrise (about 7 AM), the battery voltage begins to increase as the array current is fed into the battery. Until about noon, the array current and the battery voltage increase steadily with increasing irradiance as the battery is being charged. During this period, the battery charge controller is not regulating and nearly all the array current is fed into the battery.

Near noon, the battery voltage reaches the voltage regulation setpoint and the controller begins regulating the array current. The battery current then decreases in a jagged manner that is characteristic of the interrupting (ON/OFF) algorithm. The shunt characteristic is illustrated by the fact that the array current continues to follow the same profile as the solar irradiance, while the array voltage decreases to about 5 V.

Until regulation, the minimum and maximum battery voltages closely match the average battery voltage. During regulation, the maximum battery voltage is between 14.2 V and 14.5 V, corresponding to the voltage regulation setpoint. The minimum battery voltage is consistently about 13.6 V, corresponding to the array reconnect voltage. The minimum voltage's consistency during regulation indicates that the controller is cycling between the voltage regulation and array reconnect setpoints at least once every six minutes. The differences in the minimum and maximum battery voltages during regulation are due to the ON/OFF algorithm.

Towards the end of the afternoon (4 PM to 5 PM), the array current output reduces to a low enough value (in this case about 2.5 A) where regulation is not required. At sunset (about 6 PM), the battery voltage begins a gradual decrease to its open-circuit voltage. The open-circuit voltage at this time is higher than in the morning, indicating a higher state-of-charge. At about 8 PM, the lighting load is reconnected and the battery voltage begins to steadily decrease.





Series-Interrupting Charge Controllers

A series-interrupting charge controller completely open-circuits the array, suspending current flow into the battery. As the battery reaches full state-of-charge, a switching element inside the controller opens, moving the array's operating point on the I-V curve to the open-circuit condition and limiting the power output. When the battery voltage falls, the controller closes the series switching element to reconnect the array and resume charging the battery. Similar to shunt-interrupting charge controllers, the rate of the ON/OFF cycling is dependent on charge rate and battery state-of-charge. However, this method works in series between the array and battery, rather than in parallel as for the shunt-type controller.

During the night, the load is operating and battery voltage decreases steadily to about 11.7 V while being discharged. At about 4:30 AM, the load is disconnected by the charge controller timing circuit. At this point, the battery current goes to 0 A, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.1 V.

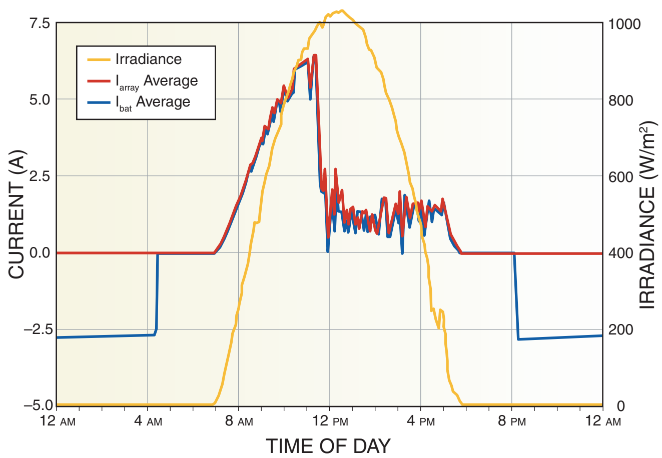
At sunrise (about 7 AM), the battery voltage begins to increase as the array current charges the battery. Until about noon, the array current and the battery voltage increase steadily with increasing irradiance as the battery charges. During this period, the battery charge controller is not regulating and the array current is approximately the same as the battery current. However, the minimum battery voltage shows values slightly lower than the average and maximum battery voltages during the morning charging period. This is a particular characteristic of this charge controller, which periodically disconnects the array from the battery to sense nighttime conditions.

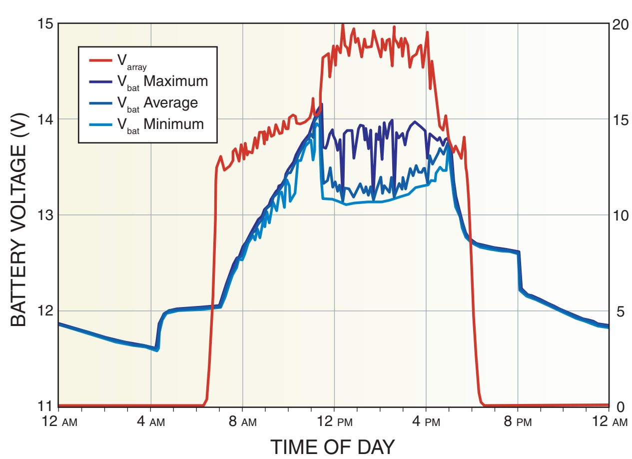
At about noon, the battery voltage reaches the voltage regulation setpoint (about 14.1 V), and the controller begins to regulate the array current. When this occurs, the battery current decreases in a jagged manner that is characteristic of the interrupting (ON/OFF) algorithm. Another characteristic of series controllers is that once regulation begins, the average array current decreases, while the average array voltage approaches the array open-circuit voltage. This controller open-circuits the array during regulation, resulting in 0 A of PV current and operating the array at the open-circuit voltage point.

With the onset of regulation, the minimum and maximum battery voltages approximately indicate the controller setpoints. The maximum battery voltage is about 14.1 V and corresponds to the voltage regulation setpoint. The minimum battery voltage is between 13.2 and 13.4 V, corresponding to the voltage at which the charge controller reconnects the array to the battery to resume charging.

At sunset (about 6 PM), the battery voltage begins a gradual decrease to its open-circuit voltage. The open-circuit voltage at this time is higher than it was in the morning before the battery was charged. At about 8 PM, the lighting load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.

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





Series-Linear Charge Controllers

A series-linear charge controller limits charging current to a battery system by gradually increasing the resistance of a series element. This limits current flow into the battery and maintains the battery at the voltage regulation setpoint (as long as array current is sufficiently high). The series regulation element acts like a variable resistor and loads the array at lower current and power levels by operating the array to the right of the maximum power point of its I-V curve. The resistance is held at a value that limits the amount of current allowed to flow from the array to the battery, while holding the array voltage at a constant value corresponding to the regulation voltage. Therefore, series-linear charge controllers are also known as constant-voltage charge controllers.

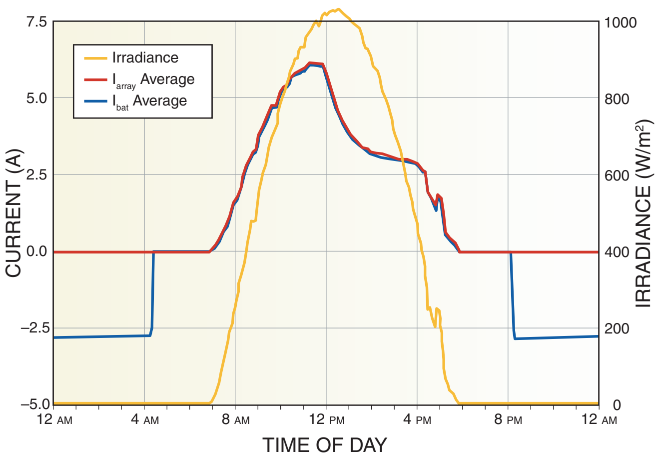
During the night, the load is operating and battery voltage decreases steadily to about 11.9 V while being discharged. At about 4:30 AM, the load is disconnected by the charge controller timing circuit. At this point, the battery current goes to 0 A, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.3 V.

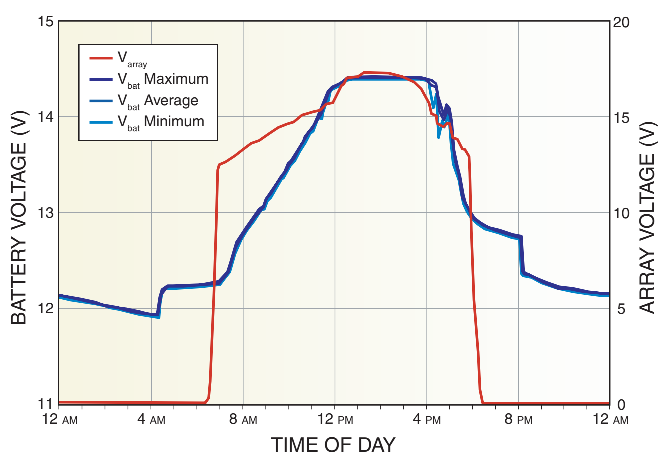
At sunrise (about 7 AM), the battery voltage begins to increase as the array current charges the battery. Until about noon, the array current and the battery voltage increase steadily with increasing irradiance as the battery charges. During this period, the battery charge controller is not regulating and the array current is approximately the same as the battery current.

At about noon, the battery voltage reaches the voltage regulation setpoint (about 14.4 V), and the controller begins to regulate the array current. When this occurs, the battery current gradually decreases. The series characteristic of this controller is indicated by the fact that once regulation begins, the average array current also decreases while the average array voltage approaches the open-circuit array voltage.

With the onset of regulation, the minimum and maximum battery voltages are indistinguishable from the six-minute average voltage, indicating that the controller is not an ON/OFF interrupting type design. After the initial regulation at 14.4 V, the voltage remains at this level through the remainder of regulation.

Near sunset (about 6 PM), the array current is no longer high enough to maintain the battery at the regulation voltage, and the battery voltage begins a gradual decrease to its open-circuit voltage. At about 8 PM, the lighting load is again reconnected and the battery voltage begins to steadily decrease until the next day when charging resumes.





Pulse-Width-Modulated Charge Controllers

A pulse-width-modulated (PWM) charge controller simulates a variable charging current by switching a series element ON and OFF at high frequency for variable lengths of time. The charge controller pulses the full charging current and varies the width of the pulses to regulate the amount of charge current flowing into the battery. The frequency of the pulses is several hundred hertz and the pulses may last only a couple of milliseconds.

When the battery is partially charged, the current pulse is essentially ON all the time. To simulate a lower charging current as the voltage rises, the pulse width is decreased to hold the battery voltage at the regulation setpoint. For example, if the pulses switch the full charging current so that it is ON half the time and OFF half the time, the resulting current effectively simulates a charge current at 50% of the full current.

In effect, the PWM design operates similar to the series-linear charge controller, with the exception that there is a small hysteresis between the minimum and maximum battery voltage after regulation. The PWM is essentially a high-switching speed, interrupting-type charge controller that does not allow the battery voltage to drop significantly during regulation.

Overnight, the load is operating and battery voltage decreases steadily to about 12.0 V while being discharged. At about 4:30 AM, the load is disconnected by the charge controller timing circuit. At this point, the battery current goes to 0 A, and there is a sharp rise in the battery voltage as it approaches an open-circuit (no load) voltage of about 12.3 V.

At sunrise (about 7 AM), the battery voltage begins to increase as the array current charges the battery. Until about noon, the array current and the battery voltage increase steadily with increasing irradiance as the battery charges. During this period, the battery charge controller is not regulating and the array current is approximately the same as the battery current.

At about noon, the battery voltage reaches the voltage regulation setpoint (about 14.5 V), and the controller begins to regulate the array current. When this occurs, the battery current decreases in a jagged manner, and remains in a current-limited mode through the remainder of the day. The series characteristic is identified by the fact that once regulation begins, the average array current also decreases while the average array voltage approaches the open-circuit array voltage.

At sunset (about 6 PM), the battery voltage begins a gradual decrease to its open-circuit voltage. At about 8 PM, the lighting load is reconnected and the battery voltage begins to steadily decrease in transition to the next day.